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APPLICATION OF THE FINITE ELEMENT PROGRAM 'ADINAT' TO ONE DIMENSIONAL CONSOLIDATION

by

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A THESIS

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致父母親

TO MY PARENTS

ABSTRACT

This thesis presents a study of the application of the finite element program ADINAT (Automatic Dynamic Incremental Nonlinear Analysis of Temperatures) to one dimensional consolidation. A few basic features of the program are reviewed, and linear and nonlinear consolidation analyses are discussed in detail. Specifically, a simple general governing equation is formulated for the primary use of predicting consolidation pore pressures.

Applications of ADINAT in pore pressure predictions are illustrated through various sample analyses. Illustrations have included a comprehensive review of relevant researches to date. Within the scope of the present study, this dissertation may serve as a state of the art manual for a general treatment of one dimensional consolidation.

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LIST OF SYMBOLS

a	constant; Lagrangian coordinate, measure in the direction of gravity
b	reduced coordinate, measure in the direction of gravity
c	energy capacity; compressibility; reduced coordinate
c'	mode of variation of the modulus of elasticity
c"	specific heat per unit volume
d	distance from water table to soil layer
e	void ratio; superscript indicating "element"
f	subscript for final value; bold type indicates load vector
g	consolidation parameter
$\bar{g}$	load vector
h	total depth of compressible layer
i	subscript refers to nodal value or counter
k	conductivity; permeability; bold type indicates vector
k_H	thermal conductivity
m	subscript denotes number of elements

$\hat{m}$ mode of variation for C_F

m_v coefficient of volume compressibility

n a constant; an outward normal to boundary surface; subscript refers to values obtained with zero void ratio

o subscript refers to the initial state

p pore water pressure; material constant

q energy flow rate per unit volume; fluid flow; applied loading; material constant

q^B rate of energy generated per unit volume

q^C rate of energy stored per unit volume

q^s boundary energy flow input to the surface S_2

r radius

s subscript for value at soil surface

t time

u excess pore pressure

v volume flow velocity; subscript indicates vertical direction

w subscript indicates water

x coordinate variable in ADINAT

z — Eulerian coordinate, measure in the direction of gravity

A — a constant; cross-sectional area; bold type for interpolation matrix

A — amplitude of sine function

B — Terzaghi's excess pore pressure ratio; bold type for gradient interpolation matrix

C — mass or compressibility matrix

C_o — material constant

Cc — slope of the $e\text{-}\log_{10}\sigma'$ line

C_F — consolidation parameter, $(1+e_o/1+e)^2Cv$

C'_F — material parameter, $(\lambda e'+1)/(\lambda+1)$

Ck — slope of the $e\text{-}\log_{10}k$ line

$C\acute{k}$ — material constant

Cv — coefficient of consolidation

C^m_v — Cv with constant m_v

Cvi — initial consolidation ratio, $k_o\sigma'_o \ln 10\ (1+e_o)/\gamma_w$ Cc

Cvo — consolidation ratio, $k_o(1+e_o)(d\sigma'/de)_o/\gamma_w$

E — modulus of elasticity of soil

F — given function; operator

G given function; operator

H initial length of vertical drainage path; subscript refers to heat

$\mathbf{K}$ symmetric matrix; conductivity matrix

K permeability variable in ADINAT

KM refers to either the permeability or the compressibility

$\mathbf{L}$ differential operator

M dimensionless number

M compressibility variable in ADINAT

N shape function; total number of solution time step

Q^g rate of energy generated

Q^i concentrated energy flow input

Q^{in} energy inflow rate

Q^{out} energy outflow rate

Q^s rate of energy stored

$\mathbf{Q}$ total nodal energy input vector

$\mathbf{Q}_B$ energy generated at the system

$\mathbf{Q}_C$ energy stored at the system

Q_s	energy transfer at the boundary surface
Q_E	externally applied nodal energy flows
S	boundary surface of the problem domain; settlement
S_1	boundary on which the unknown is prescribed
S_2	boundary on which the unknown gradient is prescribed
T	temperature; time factor; superscript denotes transpose of matrix
Tb	time factor for bottom layer
T'	time factor, C_0t/h
T_1	time factor, $(c'k\gamma_t t)/\gamma_w$
U	average degree of consolidation for the whole layer
W	weight
α	load ratio; space coordinate; time integration scheme
β	permeability ratio; space coordinate
γ	unit weight
$\overline{\gamma}_b$	average submerged unit weight of soil
γ_s	unit weight of soil solids
δ	variational operator

ϵ	mode of variation of material properties; indicates 'an element of'
ζ	self-weight ratio
$\bar{\zeta}$	average self-weight ratio
η	mode of variation of material properties
η'	material constant
θ	unknown function
θ_1	prescribed unknown function
θ^i	unknown function at boundary point
θ^s	unknown function at the boundary surface
$\bar{\theta}$	vector of the unknown function
λ	eigenvalue; material parameter, $\hat{m}e_o/(C_o-\hat{m}e_o)$
λ'	material parameter
μ	local consolidation ratio or relative degree of compression
ν	ratio of Cc/Ck
ν_r	material constant, 1/Cc - 1/Ck
ξ	strain; convective coordinate
ρ	density

σ total stress

σ' effective stress

σ'_0 initial effective stress in soil, before loading is applied

τ dimensionless time factor, $Cvi \cdot t/H^2$

ϕ subscript for initial value at surface (before loading is applied)

χ diffusivity

ω variable of $\log_{10}(\sigma'/\sigma'_f)$

ς material parameter

Δ prefix indicates a finite increment

Θ space coordinte denotes either a or z

Π a stationary functional

Σ summation

Ω bounded problem domain

§ characteristic number

ℓ reduced thickness of soil layer

$\imath$ subscript or superscript refers to the $\imath$th layer

1 subscript refers to an arbitrary reference state

∞	indicates the final value at layer bottom
$'$	superscript prime denotes coordinate differentiation
'	quote mark refers to a ratio of the original value
$\cdot$	superposed dot denotes time differentiation
$\_$	upper underscore indicates mean value or trial function

1. INTRODUCTION

1.1 General

The majority of phenomena arising in engineering and physics are often described by differential equations, especially by partial differential equations, and by boundary conditions imposed on the unknown functions.

Seepage through porous media, heat conduction and torsion are three important phenomena governed essentially by differential equations of similar form, particularly the diffusion, Laplace and Poisson equations. These problems are often known as *field problems*, and the general governing equation is called a *field governing equation*.

Some other examples of this type of problem include gravitational and irrotational fluid flow, surface waves on a fluid, natural frequency of footings, heat convection, electrostatics, magnetostatics and electrical currents. (Desai and Abel, 1972)

ADINAT, a general purpose computer program which employs the parabolic differential equation of the heat conduction type, can be used to solve many of these field problems.

Since finding closed-form solutions for the more general cases can be difficult, various methods of computing approximate solutions have been developed. Among these, the energy method, or variational method, has gained considerable popularity. The finite element formulation, which is modified from the classical variational method, became widely used with the advent of computers.

ADINAT employs the variational procedure in deriving the finite element equations. The high accuracy of the program and its incremental solution procedure are particularly applicable to problems with soils, where nonlinear constitutive relations are fundamental and intrinsic.

Consolidation is the process of gradual reduction in volume of a soil mass of low permeability due to the dissipation of excess pore water pressure. The one dimensional consolidation condition occurs either with a large uniformly loaded area or with lateral physical constraints. One dimensional consolidation theory is extensively used in practice for pore pressure predictions, settlement and stability analyses.

The conventional consolidation analysis is based on the classical Terzaghi theory. Despite the simplifying assumptions embodied in the theory, it is still widely

employed in practice due to its simplicity. It also permits extensions in a simple way to cover other situations.

An example of an earlier extension is the nonhomogeneous problem. It is often approximated as discrete layers of unlike soils, in each of which the material properties are reasonably uniform. Continuous spatial variation of material properties, is another simple method to simulate the varying material properties in soils. The latter is, however, a step closer to a *nonlinear* analysis.

The term 'nonlinear' here refers to the condition of nonlinear constitutive relationships, or of material properties which basically vary with time.

One dimensional nonlinear consolidation studies were developed by 1965. Barden and Berry (1965), Davis and Raymond (1965), Janbu (1965), Mikasa (1965), Raymond (1966 & 1969), Gibson *et al* (1967), Poskitt (1969), Davis (1971) provided prominent nonlinear theories at that time. Gibson *et al* published a general theory removing many of the simplifying assumptions in the conventional analysis, and included the effects of both finite strain and self-weight. Extensions to this theory have been made by other researchers. (Poskitt, 1969; Simons and Beng, 1969; Monte and Krizek, 1976; DeSimone and Viggiani, 1976; Gibson *et al*,

1981)

Due to mathematical difficulties, recourse has been made by most nonlinear theories to further approximations in order to derive solutions.

Finite element solutions are provided by ADINAT for various nonlinear analyses. Detailed discussions of the application of the program to nonlinear consolidation will be presented in this thesis.

1.2 Scope of Research

The basic aim of this thesis is a general study of ADINAT application in one dimensional consolidation. Necessary steps to achieve this goal are outlined below:

1. Examination of basic features in ADINAT;
2. Thorough review of consolidation theories;
3. Assessment of available models applicable to ADINAT;
4. Formulation of the appropriate model compatible with the illustrative theory.
5. Simulation of ADINAT input and preparation for the results.
6. Evaluation of the use of ADINAT in such analysis.

Steps 3 to 6 are repeatedly used throughout this thesis.

The consolidation studies here are limited by the assumptions stated in the following chapters. The studies can be divided into two parts. The first part deals with linear and nonhomogenous problems, in which Terzaghi's simplifications are generally applied. The second part is concerned with nonlinear analyses, where assumptions such as the validity of Darcy's law and constant load increments are accepted but stress history and secondary effects are neglected.

Applications of ADINAT are illustrated through sample analyses selected from various areas of the program applicability. Predictions of pore pressures are the primary concern in these examples. The guidelines given below are followed in the development of the examples:

a. Simplicity and brevity;
b. Usefulness, in the sense that each example represents a certain type of formulation;
c. Correctness in modelling, by presenting the required derivation and a comparison with published formulations and/or experimental results;
d. Correctness in computation, by comparison with closed-form or published results where available;

e. Completeness; the main reasons for those not illustrated are: similarity, duplication, inadequate data, no practical solution exists or the analyses are outside the scope of the assumptions.

A brief discussion of the governing equation and several features in ADINAT are given in Chapter 2. Chapter 3 deals with the application of ADINAT to linear problems. Conventional analysis, as well as homogenous layered and continuous nonhomogeneous problems, are considered.

In view of the variety of soil stratigraphy, loading and boundary conditions that exist in nature, uses of ADINAT in different physical situations will also be illustrated and given with the examples.

A brief review of theories and discussions on the use of ADINAT in nonlinear analyses are presented in Chapter 4. A collection of equations are given for a general treatment of these analyses. These equations are tabulated for convenience in use and reference. Chapter 5 and 6 are devoted to examples of various published nonlinear theories.

2. BRIEF DESCRIPTION OF ADINAT

The governing equation in ADINAT will be discussed below. Mass matrix or compressibility matrix analysis and the time integration scheme of the program will be briefly discussed. Stability and accuracy requirements in using the program are also given.

2.1 Governing Field Equation

The general field equation solved by ADINAT, for a problem domain idealized as an assemblage of finite elements, can be interpreted physically as a mathematical statement of the energy equilibrium at the nodes of the system at any time, that is (Wilson, Bathe and Peterson, 1974; Holman, 1976)

$$Q^{in} + Q^{g} = Q^{out} + Q^{s} \qquad (2.1)$$

in which

Q^{in} : rate of energy flow into the elements adjacent to the node and into the node from an external source,

Q^{g} : rate of energy generated within the elements adjacent to the node,

Q^{out} : rate of energy flow out of the elements adjacent to the node,

Q^{s} : rate of energy stored within the elements adjacent to the node.

Let θ denote the unknown function or the state variable, which can be fluid head or potential, stream function, velocity potential, temperature, warping, stress function, electrical potential and so on. The energy flux, $q_z dz$, is generally related to the gradient of θ. In considering the one dimensional condition, a very general relationship in terms of the proportionality constant, termed conductivity k_z, is:

$$q_z dz = v_z \rho_z = -k_z \frac{\partial \theta}{\partial z} \tag{2.2}$$

where v_z is the flow velocity and ρ_z is the density. This can also be expressed by similar equations as those shown below using the appropriate physical law for a given problem. For instance, from Darcy's law

$$q_z dz = v_z \gamma_w = -k_z \frac{\partial u}{\partial z} \tag{2.3}$$

or from Fourier's law of heat conduction

$$q_z dz = -k_z \frac{\partial T}{\partial z} \tag{2.4}$$

where u is the fluid pressure, T is the temperature, k_z is the hydraulic conductivity in Eq. 2.3 and the thermal conductivity in Eq. 2.4. Hence, Q^{in} can be determined by

$$Q^{in} = -k_z A_z \frac{\partial \theta}{\partial z} \tag{2.5}$$

Similarly,

$$Q^{out} = -k_z A_z \frac{\partial \theta}{\partial z}\bigg|_{z+dz}$$

$$= -A_z \left[k_z\frac{\partial\theta}{\partial z} + \frac{\partial}{\partial z}(k_z\frac{\partial\theta}{\partial z})dz \right] \tag{2.6}$$

and

$$Q^g = q^B \cdot A_z \cdot dz \tag{2.7}$$

$$Q^s = q^C \cdot A_z \cdot dz \tag{2.8}$$

q^B is the rate of energy generation per unit volume while q^C is the rate of energy stored per unit volume. Combining the above relations gives,

$$\frac{\partial}{\partial z}(k_z\frac{\partial\theta}{\partial z}) = q^C - q^B \tag{2.9}$$

Generalizing this equation in three dimensions yields:

$$\frac{\partial}{\partial x}(k_x\frac{\partial\theta}{\partial x}) + \frac{\partial}{\partial y}(k_y\frac{\partial\theta}{\partial y}) + \frac{\partial}{\partial z}(k_z\frac{\partial\theta}{\partial z}) = q^C - q^B \tag{2.10}$$

where k_x, k_y, k_z are the conductivities corresponding to the x, y, z directions.

The associated boundary conditions are

$$\theta = \theta_1 \tag{2.11}$$

on part of the boundary S_1 of the domain, while

$$k_n \frac{\partial \theta}{\partial n} = q^s \tag{2.12}$$

on part of the boundary S_2 of the problem domain, and

$$\theta|_{t=0} = \theta_0 \tag{2.13}$$

n denotes the outward normal to the surface. θ_1, q^s are the prescribed values of the unknown and energy flow input to the boundary surface respectively. θ_0 is the initial value of the unknown θ.

2.2 Variational Method

2.2.1 Variational Principle

A *variational principle* specifies a scalar quantity expressed in an integral form (Desai and Abel, 1972; Zienkiewicz, 1977)

$$\Pi = \int_{\Omega} F(x,y,z,\theta,\theta',\theta'',\ldots)d\Omega + \int_{S} G(\theta,\theta',\ldots)dS \qquad (2.14)$$

in which θ is the unknown variable or function, the superscript prime denotes differentiation with respect to the cartesian coordinates, the number of primes is the order of differentiation. Ω is the bounded problem domain and S is its piecewise smooth boundary, F and G are specified operators. Π is called a functional, because it is a function of other functions.

The boundary conditions can be sorted into three classes: the essential, natural and mixed boundary conditions. For quadratic functionals, where the operators contain at most second order derivatives, essential boundary conditions are the prescribed values of the unknown function θ. The natural boundary conditions correspond to the first order derivatives of the unknown function, $\partial\theta/\partial n$. n denotes

one of the coordinate direction x, y, z, or the direction of the outward normal to the boundary surface. The mixed boundary condition is a combination of the above two.

In the variational procedure, tentative solutions, or trial functions, $\overline{\theta}$, satisfying the essential boundary conditions are tried for a given problem,

$$\theta \simeq \overline{\theta} = \Sigma N_i a_i \tag{2.15}$$

where N_i are base functions prescribed in terms of independent variables such as the coordinates x, y, z. Parameters a_i are unknown constants.

From all such possible solutions, the solution to the problem will be the one which makes the functional Π stationary, that is

$$\delta\Pi = 0 \tag{2.16}$$

with respect to small changes $\delta\theta$, where

$$\overline{\theta} = \theta + \delta\theta \tag{2.17}$$

δ is the variation notation, termed the 'variation in'.

From calculus of variations,

$$\delta\Pi = \frac{\partial\Pi}{\partial a_1}\,\delta a_1 + \frac{\partial\Pi}{\partial a_2}\,\delta a_2 + \ldots = \frac{\partial\Pi}{\partial \mathbf{a}}\,\delta\mathbf{a} \tag{2.18}$$

Since the stationary condition of Π in Eq. 2.16 is true for any arbitrary $\delta\mathbf{a}$, then

$$\frac{\partial\Pi}{\partial\mathbf{a}} = 0 \tag{2.19}$$

which yields a set of equations for the parameters $\mathbf{a}$. Note that if the functional Π is quadratic, or the derivatives of the unknown function θ do not exceed second order, Eq. 2.19 reduces to a set of linear equilibrium equations of the form (Zienkiewicz, 1977)

$$\mathbf{Ka} + \mathbf{f} = 0 \tag{2.20}$$

$\mathbf{f}$ is the action vector, and the matrix $\mathbf{K}$ will always be symmetric. Hence the parameters a_i are easily computed, and an approximate solution for the problem can be found.

The essence of the variational method is, therefore, to establish the functional Π of the problem, choose a trial function $\bar{\theta}$ and find the stationary value of Π, that is $\delta\Pi = 0$.

This approximation process using trial functions and stationary conditions is known as the Rayleigh-Ritz method. The finite element form of this method employs several simple trial functions $\bar{\theta}^e$, each defined only over an element of a discretized domain, instead of using a single trial function which spans the entire domain as in the classical method. This piecewise fit is the basic feature of finite element analysis.

The appropriate functional for a given problem can be established in a number of ways. It can be derived vigorously using some theorems as guidelines, or obtained backward from the governing differential equations and natural boundary conditions with mathematical manipulation. Generally, there does not exist a unique functional for a

particular problem. A specific functional, however, can be applicable to a certain class of problems. (Bathe, 1982)

2.2.2 General Formulation

A linear system of differential equations can be written as

$$\mathbf{L}\bar{\theta} + \bar{g} = 0 \tag{2.21}$$

where $\bar{\theta}$ is the vector of the unknown variable, and $\bar{g}$ is the known action function. If the differential operator $\mathbf{L}$ is linear and self-adjoint, it can be shown that the variation principle is given as (Zienkiewicz, 1977)

$$\Pi = \int_{\Omega} [(1/2)\bar{\theta}^T \mathbf{L}\bar{\theta} + \bar{\theta}^T \bar{g}]d\Omega + \text{Boundary Terms} \tag{2.22}$$

the superscript T stands for the transpose.

Applying this to Eq. 2.10 and using integration by parts, the functional of the field equation is then (Bathe, 1982)

$$\Pi = \int_{\Omega} \frac{1}{2}\left[k_x\left(\frac{\partial\theta}{\partial x}\right)^2 + k_y\left(\frac{\partial\theta}{\partial y}\right)^2 + k_z\left(\frac{\partial\theta}{\partial z}\right)^2 \right] d\Omega$$

$$- \int_{\Omega} \theta(q^B - q^C)\, d\Omega - \int_{S_2} \theta^s q^s\, dS - \sum_i \theta^i Q^i \qquad (2.23)$$

where θ^s, θ^i are the unknown functions at the boundary surface. Q^i is the concentrated energy flow input.

The functionals in engineering problems usually possess physical meaning. (Zienkiewicz *et al*, 1966) The first integral of the above functional, may be interpreted as the rate at which energy is being dissipated over the entire domain, where,

$$-\left[k_x\left(\frac{\partial\theta}{\partial x}\right)^2 + k_y\left(\frac{\partial\theta}{\partial y}\right)^2 + k_z\left(\frac{\partial\theta}{\partial z}\right)^2\right] = v_x\frac{\partial\theta}{\partial x} + v_y\frac{\partial\theta}{\partial y} + v_z\frac{\partial\theta}{\partial z} \qquad (2.24)$$

is proportional to the energy dissipation rate in a unit volume. The fact that the unknown θ system gives the

minimum value of this integral which corresponds to the exact solution, is consistent with the principle of minimum potential energy.

From Eq. 2.16 and Eq. 2.23, and since θ is the only variable, it can be shown that (Bathe, 1982)

$$\int_{\Omega} \delta(\bar{\theta}')^{T} \mathbf{k}\bar{\theta}' d\Omega$$

$$= \int_{\Omega} \delta\theta(q^{B} - q^{C}) d\Omega + \int_{S_2} \delta\theta^{s} q^{s} dS + \sum_{i} \delta\theta^{i} Q^{i} \qquad (2.25)$$

in which

$$(\bar{\theta}')^{T} = \left[\frac{\partial\theta}{\partial x} \quad \frac{\partial\theta}{\partial y} \quad \frac{\partial\theta}{\partial z} \right] \qquad (2.26)$$

$$\mathbf{k} = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix} \qquad (2.27)$$

Consider the whole problem domain, for any element

$$\theta = \mathbf{A}\,\bar{\theta} \tag{2.28}$$

$$\bar{\theta}' = \mathbf{B}\,\bar{\theta} \tag{2.29}$$

where **A** and **B** are the element θ and θ-gradient interpolation matrices respectively. Assume the rate of energy storage is given by

$$q^{c} = c\dot{\theta} \tag{2.30}$$

the proportional constant c is called energy capacity (or volume compressibility). A superposed dot indicates time differentiation. The variation in θ, $\delta\theta$, in Eq. 2.25 can be considered as a virtual quantity and the equation is analogous to the virtual work equation in structural stress analysis. Hence the system governing energy equilibrium equations can be written as (Bathe, 1982)

$$\mathbf{C}\dot{\bar{\theta}} + \mathbf{K}\bar{\theta} = \mathbf{Q} \tag{2.31}$$

in which **C** is the finite element system capacity matrix,

$$C = \sum_m \int_\Omega A^T cA \, d\Omega \tag{2.32}$$

m is the number of elements in the discretized problem domain. **K** is the conductivity matrix of the system,

$$K = \sum_m \int_\Omega B^T kB \, d\Omega \tag{2.33}$$

Q is the total nodal point energy input,

$$Q = Q_B - Q_C + Q_s + Q_E \tag{2.34}$$

where

$$Q_B = \sum_m \int_\Omega A^T q^B \, d\Omega \tag{2.35}$$

$$Q_C = \sum_m \int_\Omega A^T q^c \, d\Omega \tag{2.36}$$

$$Q_s = \sum_m \int_{S_2} A^T q^s dS \tag{2.37}$$

Q_E is a vector of externally applied nodal energy flows. **C** and **K** are constant matrices in linear steady analysis.

For nonlinear or transient problems, **C** and **K** may be either θ or time dependent or both, as

$$\mathbf{C}(\theta,t)\cdot\dot{\bar{\theta}} + \mathbf{K}(\theta,t)\cdot\bar{\theta} = \mathbf{Q}(t) \tag{2.38}$$

where t denotes time.

2.3 A Note on The Lumped and Consistent Matrix Analyses

Two types of matrix analysis options, the lumped and consistent matrix method, are available in ADINAT. Some of their basic features are briefly described in this section.

2.3.1 Consistent Matrix

Application of the standard finite element method to the energy equilibrium equation produces the capacity matrix **C** in the form of Eq. 2.32. This matrix is called *consistent* because it is derived from a procedure according to the variational formulation. (Desai, 1979) The resulting matrix is non-diagonal. The term *consistent* is thought to be

unnecessary since it is the natural outcome of the discretization process. (Zienkiewicz, 1977)

The principle advantage of the consistent matrix method is to provide a more rational analysis. However, its use does not always lead to improved accuracy but always involves additional computational work compared to the lumping method. (Desai and Abel, 1972; Zienkiewicz, 1977)

In the frequency analysis using the consistent matrix approach, more accurate mode shapes and upper-bound frequencies are obtained. (Desai and Abel, 1972)

2.3.2 Matrix Lumping Approach

An alternative way of establishing an approximate matrix **C** is by physical reasoning. As such, the matrix is assembled in an arbitrary manner by assuming that all the C values tributary to a node is lumped at that node, thus a diagonal matrix always results although no actual concentrated values exist. This matrix is often referred to as lumped matrix. (Zienkiewicz, 1977)

The resulting diagonal matrix in the conventional lumped matrix approach leads to a simple technique of formulation and solution. In addition, the lumped matrix

utilizes less storage space. This method is hence significantly more convenient and economical for many computational processes compared to the consistent matrix approach. (Zienkiewicz, 1977)

But if a coarse finite element mesh is used the result obtained may be very inaccurate. Surprising solutions may also result in some cases when high-order elements are employed. (Bathe, 1982)

The lumping scheme, nevertheless, can often be constructed so that there will be no accuracy loss. Reseachers have found some matrix lumping techniques that improve accuracy. (Fried and Malkus, 1975; Hinton, Rock and Zienkiewicz, 1976; Zienkiewicz, 1977)

The consistent and lumped matrix option can be found in ADINAT users manual input section II.2.

2.4 Remark on the Time Integration Scheme

2.4.1 General

For transient analysis, a one parameter (α) family of one-step numerical time integration method is employed in

ADINAT. This method, as in the general incremental procedure, assumes that the unknown functions at time t_n have been determined and that they are to be computed at time $t_n+\Delta t$, where t_n is the time at time n, $n\epsilon\{0, 1, ..., N-1\}$, N is the total number of solution time steps and Δt is the time step interval.

To evaluate the unknown functions at time $t_n+\Delta t$, the energy equilibrium of the problem domain is considered at time $t_n+\alpha\Delta t$. From Eq. 2.38, (Bathe and Khoshgoftaar, 1979; Bathe, 1981)

$$C(\theta_{t1},t_1)\dot{\bar{\theta}}_{t1} + K(\theta_{t1},t_1)\bar{\theta}_{t1} = Q(t_1) \tag{2.39}$$

$$\dot{\bar{\theta}}_{t1} = (\bar{\theta}_{n+1}-\bar{\theta}_n)/\Delta t \tag{2.40}$$

$$\bar{\theta}_{t1} = (1-\alpha)\bar{\theta}_n + \alpha\bar{\theta}_{n+1} \tag{2.41}$$

$$\bar{\theta}|_{t=0} = \bar{\theta}_0 \tag{2.42}$$

In the above equations t_1 denotes $t_n+\alpha\Delta t$, or $(n+\alpha)\cdot\Delta t$. Subscripts n and n+1 denote the time of t_n and $t_n+\Delta t$ respectively. $\bar{\theta}_0$ is the prescribed value at the initial state.

Note that α is a constant that ranges from 0 to 1. The value of α for a given problem is chosen to obtain optimum stability and accuracy.

Some known integration procedures such as Euler's foreward method, the trapezoidal rule, and Euler's backward method correspond to α values of zero, 1/2, and 1 respectively. These options are shown in ADINAT users manual input section II.5.

2.4.2 Stability

The properties of the integration method depend on the value of α that is used. They can be analysed by considering a typical single degree-of-freedom equilibrium equation, (Hughes, 1977; Bathe and Khoshgoftaar, 1979; Bathe, 1982)

$$\dot{\theta} + \lambda(\theta,t)\cdot\theta = 0 \qquad (2.43)$$

where λ can be considered as a ratio related to k and c. The characteristic equation of the recursion relation is obtained by using similar procedures from Eq. 2.39 to

Eq. 2.42 and solving for the unknown function θ at time $t_n+\Delta t$,

$$\theta_{n+1} = \S \cdot \theta_n$$

$$= \left[\frac{1-(1-\alpha)\Delta t \lambda_{t1}}{1+\alpha \Delta t \lambda_{t1}} \right] \theta_n \qquad (2.44)$$

where for stability, it is required

$$|\S| \leq 1 \qquad (2.45)$$

From this, the following results can be observed:

First, for $1/2 \leq \alpha \leq 1$, the above relationship is always satisfied for any Δt, which means that the integration method is unconditionally stable.

Second, for $0 \leq \alpha < 1/2$, the relation in Eq. 2.45 is satisfied provided

$$\Delta t \leq 2/\{(1-2\alpha) \cdot \lambda_{t1}\} \qquad (2.46)$$

that is, the method is conditionally stable.

Therefore, the conditionally stable methods, particularly the explicit scheme (α=0), will always result in instability as long as the time interval Δt exceeds that specified by the highest eigenvalue in the problem. The time saving computation in the explicit scheme may, however, compensate the requirement of using many small time steps.

2.4.3 Accuracy

The accuracy of the Euler forward method (α=0), the trapezoidal rule (α=1/2), the Euler backward method (α=1) can be assessed using the Taylor series expansion. (Hughes,1977; Bathe and Khoshgoftaar, 1979; Snyder and Bathe, 1981)

It can be shown that, both of the Euler methods are first-order accurate whereas the trapezoidal rule is second-order accurate. The remaining α schemes can also be shown to possess first-order accuracy. Hence, the trapezoidal rule is the only second-order accurate method in the α-family of integration scheme.

The α values with the largest error would be $\alpha=0$ and $\alpha=1$. In the Euler backward scheme ($\alpha=1$), the truncated terms in the time derivative equation obtained from Taylor's expansion are alternate in sign, which may result in significantly better solution accuracy.

2.4.4 Oscillation Effect

The following important property should also be considered in the evaluation of the different integration schemes in the α-family method. Refer to Eq. 2.44 in the previous section, oscillatory solutions will result as the characteristic value § becomes negative (Zienkiewicz, 1977). Assume that $[C^{-1}][K]$ of Eq. 2.31 has a complete set of orthogonal eigenvectors with corresponding eigenvalues λ_i, there will be no oscillation effect provided that (Wood and Lewis, 1975)

$$\Delta t < 1/\{(1-\alpha)\lambda_i\} \tag{2.47}$$

for all λ_i, or

$$\Delta t < \Delta t_{critical} = 1/\max \lambda_i \tag{2.48}$$

In each integration scheme for which $\alpha<1$, there exists a time interval beyond which § becomes negative or violates Eq. 2.47. Thus the Euler backward method ($\alpha=1$) is the only one not showing this oscillation phenomena. The predicted solutions using this method converge monotonically to the exact solution as the time interval Δt decreases.

Experience shows that, the time interval required for an accurate solution in the Euler forward method is considerably smaller than the value for stability. Even if the trapezoidal rule shows a higher order accuracy mathematically, it can give less accurate results than Euler backward method for larger time intervals. (Bathe and Khoshgoftaar, 1979)

The critical time interval in Eq. 2.48 is related to the number of degrees-of-freedom. As the number of degrees-of-freedom increases due to the increases in the complexity of the problem or the base functions, the critical time interval becomes proportionately smaller. Therefore, it is impractical to eliminate oscillations by reducing time intervals. (Wood and Lewis, 1975)

The procedure with α=2/3, named the Galerkin scheme, has been shown to be practical as a compromise between accuracy and oscillation effects. Another optimal scheme, with $\alpha=0.878 \simeq 7/8$ was also suggested by Lambert (1973), using different reasoning. (Zienkiewicz, 1977)

Wood and Lewis (1975) have illustrated that the Crank-Nicholson scheme with a simple averging process is effective in dealing with oscillations. They also observed that parabolic and cubic finite elements give better performance for accuracy and damping oscillations than linear elements, particularly with smaller time intervals.

2.5 Discussion

Eq. 2.10 is the basic governing equation in ADINAT. Various field problems can be analysed using the program by manipulating the variables k, θ, q^B and q^C. These may be consolidation, seepage, and problems in oil sands and cold region engineering, specifically in the area of geotechnical use.

In the present work, illustrations will be given for the case of one dimensional consolidation. q^B is then set equal zero and Eq. 2.30 is employed. There is no applied

mass flow loadings and hence they will be ignored in the program input.

Notice that the stationary value of Eq. 2.23 not only includes the governing equation but also the natural boundary condition. Hence, for the ADINAT input, only the essential boundary conditions are required to be explicitly specified, since the natural boundary conditions are automatically incorporated in the formulation when using the variational approach. This is particularly effective in the analysis of the problems with complicated boundaries.

Regarding the essential boundary conditions, nodes at impervious boundaries are deleted as degrees of freedom in the input stage. This simply means that the equilibrium equations Eq. 2.31 will not be considered for these nodes. (see ADINAT users manual input section IV)

The neglecting of natural boundary conditions input and the mechanical generation of system equilibrium equations, as shown in Section 2.2, are the primary advantages of the variational approach as used by the program.

The value of α used in the following examples is 1 (implicit scheme), mainly for reasons of stability. Other choices of α values may provide better results, depending on the given problems. Examples showing the use of α values

other than 1 can be found in Part B of the program manual.

The equilibrium iteration scheme used by ADINAT is the modified Newton-Raphson method. The number of time steps between equilibrium iterations, maximum number of iteration cycles and allowable tolerance for convergence are described in the program manual and input in control card II.4.

3. LINEAR APPLICATION OF ADINAT IN ONE DIMENSIONAL CONSOLIDATION

The application of ADINAT's linear capability in one dimensional consolidation will be illustrated in this chapter. Examples will include Terzaghi's classical theory, homogeneous layered and continuous nonhomogeneous problems.

3.1 Terzaghi Classical Theory

3.1.1 General

The classical theory of one dimensional consolidation of clay deposits was developed by Karl Terzaghi in 1925. It is founded on the following basic assumptions:

1. The soil is homogeneous and is saturated.
2. The soil grains and pore fluid are incompressible in comparison with the soil skeleton, and volume change is the result of changes in void ratio.
3. The average fluid flow and compression are one dimensional.
4. The surface applied load causes a uniform increment of vertical total stress throughout the soil layer.
5. Darcy's law of permeability is valid at all hydraulic gradients and in the form of the average

fluid flow velocity related to the excess pore pressure gradient.

6. The stress history of the soil stratum is ignored.
7. The structural viscosity effects, which control secondary compression or creep, are ignored.
8. All initial total stresses are uniformly distributed throughout the soil stratum.
9. The void ratio is a unique linear function of the effective stress and is independent of time, that is, the coefficient of volume change is constant.
10. The coefficient of permeability remains constant throughout the consolidation process.
11. Strains, velocities and stress increments are small.
12. The soil layer is comparatively thin such that the stresses arising from the self-weight of the solids and pore fluid are negligible compared with those applied.

By equating the volume of pore water expulsion with the reduction in void volume of a soil element, Terzaghi established the following governing equation for one dimensional consolidation:

$$C_v \frac{\partial^2 u}{\partial z^2}(z,t) = \frac{\partial u}{\partial t}(z,t) \tag{3.1}$$

where Cv is the coefficient of consolidation, u is the excess pore pressure, z is the vertical distance from the nearest drainage boundary to the element under consideration.

Eq. 3.1 defines the immediate magnitude of the excess pore pressure u in an element at a specific distance z in the soil mass at time t, after an instantaneous application of a time-independent load Δq. Since the load causes a uniform stress increment, $\Delta\sigma_v$, the initial excess pore pressure is

$$u(z,0) = \Delta\sigma_v = \Delta q \tag{3.2}$$

Hence the excess pore pressure u for a clay layer subjected to double drainage can be expressed as (Taylor, 1948)

$$u(z,t) = \sum_{m=0}^{\infty} \frac{2u_0}{M} \sin\frac{Mz}{H} e^{-M^2 T_v} \tag{3.3}$$

where $M=\pi(2m+1)/2$ and m is any integer from 0 to ∞. The boundary conditions are, for double drainage,

$$u(0,t) = 0 \tag{3.4}$$

$$u(h,t) = 0 \tag{3.5}$$

for single drainage, Eq. 3.5 becomes

$$\frac{\partial u}{\partial z}(H,t) = 0 \tag{3.6}$$

where H is the minimum drainage path. Note that Cv is generally expressed as,

$$Cv = \frac{k}{\gamma_w m_v} \tag{3.7}$$

k is the coefficient of permeability and m_v is the coefficient of volume compressibility, which is defined by

$$m_v = -\frac{1}{1+e} \cdot \frac{de}{d\sigma'} \tag{3.8}$$

The term (1+e) in the above equation is assumed to be equal to $(1+e_0)$ in this chapter. The average consolidation U for the entire stratum in linear theory is determined as

$$U = 1 - \frac{\int u(z,t)dz}{\int u(z,0)dz} \tag{3.9}$$

The above integrals are evaluated for the entire compressible layer. Substituting Eq. 3.2 and Eq. 3.3 into Eq. 3.9 gives

$$U = 1 - \sum_{m=0}^{\infty} \frac{2}{M^2} e^{-M^2 Tv} \tag{3.10}$$

The analogies between the heat transfer equation in ADINAT and the consolidation equation can be seen below,

Heat Transfer: $$k_H \frac{\partial^2 T}{\partial z^2} = \rho c \frac{\partial T}{\partial t} \qquad (3.11)$$

Consolidation: $$k \frac{\partial^2 u}{\partial z^2} = \gamma_w m_v \frac{\partial u}{\partial t} \qquad (3.12)$$

k_H is the thermal conductivity.

The input and output parameters of ADINAT can be deduced from the above comparison. It is worthwhile to mention that in the program, the product of ρ and c forms a single variable c", which is the specific heat per unit volume.

3.1.2 Sample Analysis

Objective:

To illustrate the application of ADINAT to Terzaghi's one dimensional consolidation theory and predict the pore pressure distribution in a simple soil layer.

Problem Description:

A simple single layer with drainage at both top and bottom is shown in Fig. 3.1. The applied loading and the material properties used in the analysis are given in the figure.

Finite Element Model:

For the finite element analysis, ten equal length one dimensional linear elements have been used. The consistent compressibility matrix option and the Euler backward method for time integration have been chosen for computation.

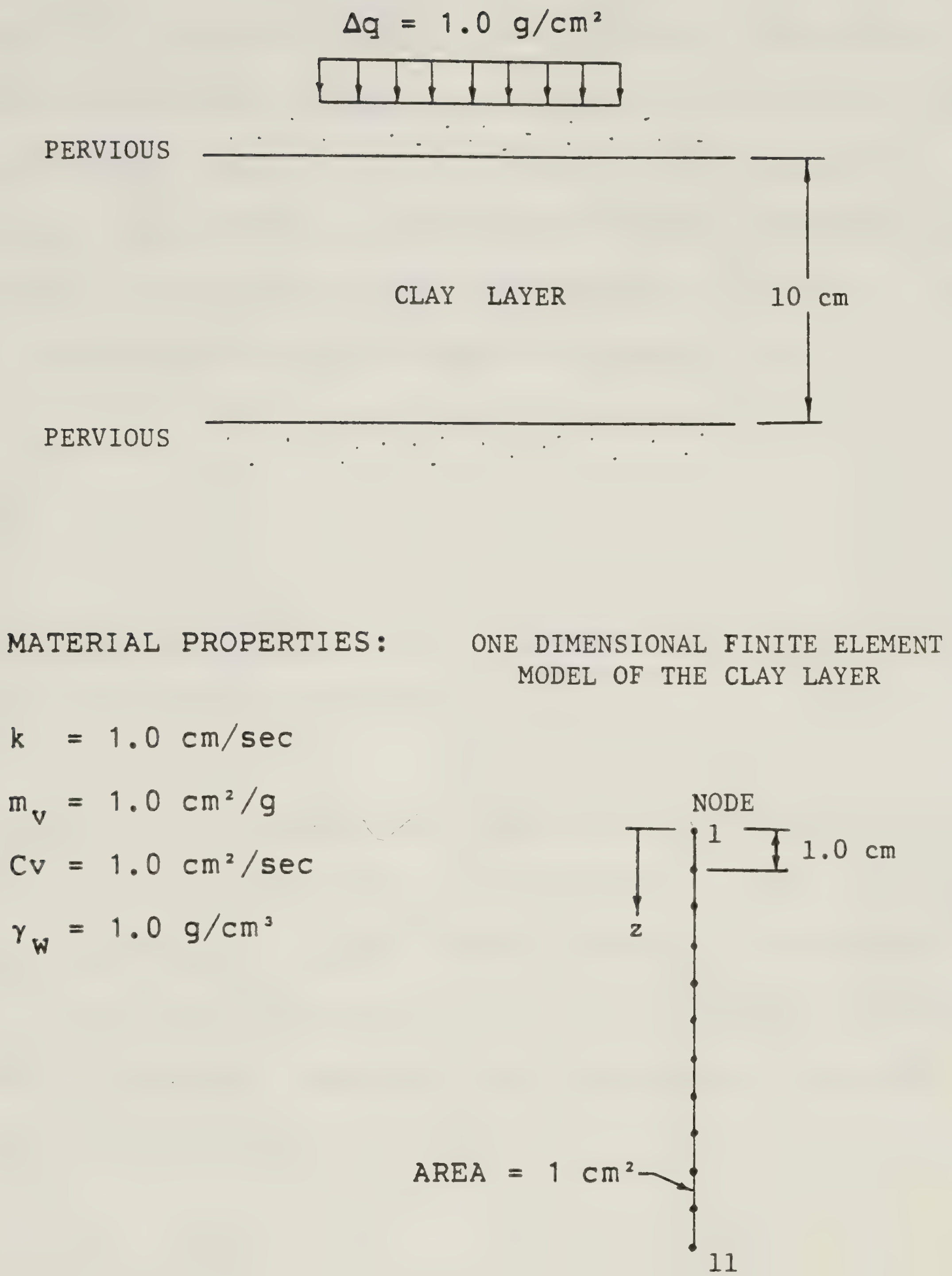


Figure 3.1 Analysis of one dimensional consolidation with double drainage

Solution Results:

Fig. 3.2 shows the excess pore pressure isochrones predicted by ADINAT at time factors 0.1, 0.4 and 0.9. Only one half of the layer is shown because of the symmetry condition. Closed-form solution of Terzaghi's analysis is also given in the figure and good agreement is shown. The ADINAT input datafile is enclosed in Appendix A.1.

Remarks:

The computer program used to compute the closed-form solutions is given in Appendix B.1.

A listing of ADINAT input datafile for the case of the impervious base is included in Appendix A.1. The physical problem, loading and finite element model is the same as above, except the thickness now is 5 cm. The pore pressure results, as would be expected, are the same as the upper half layer of the previous case.

User Hints:

a. For the case of double drainage, the initial conditions are applied to all but the top and bottom nodes, at which the deleted (*zero*) pressure condition

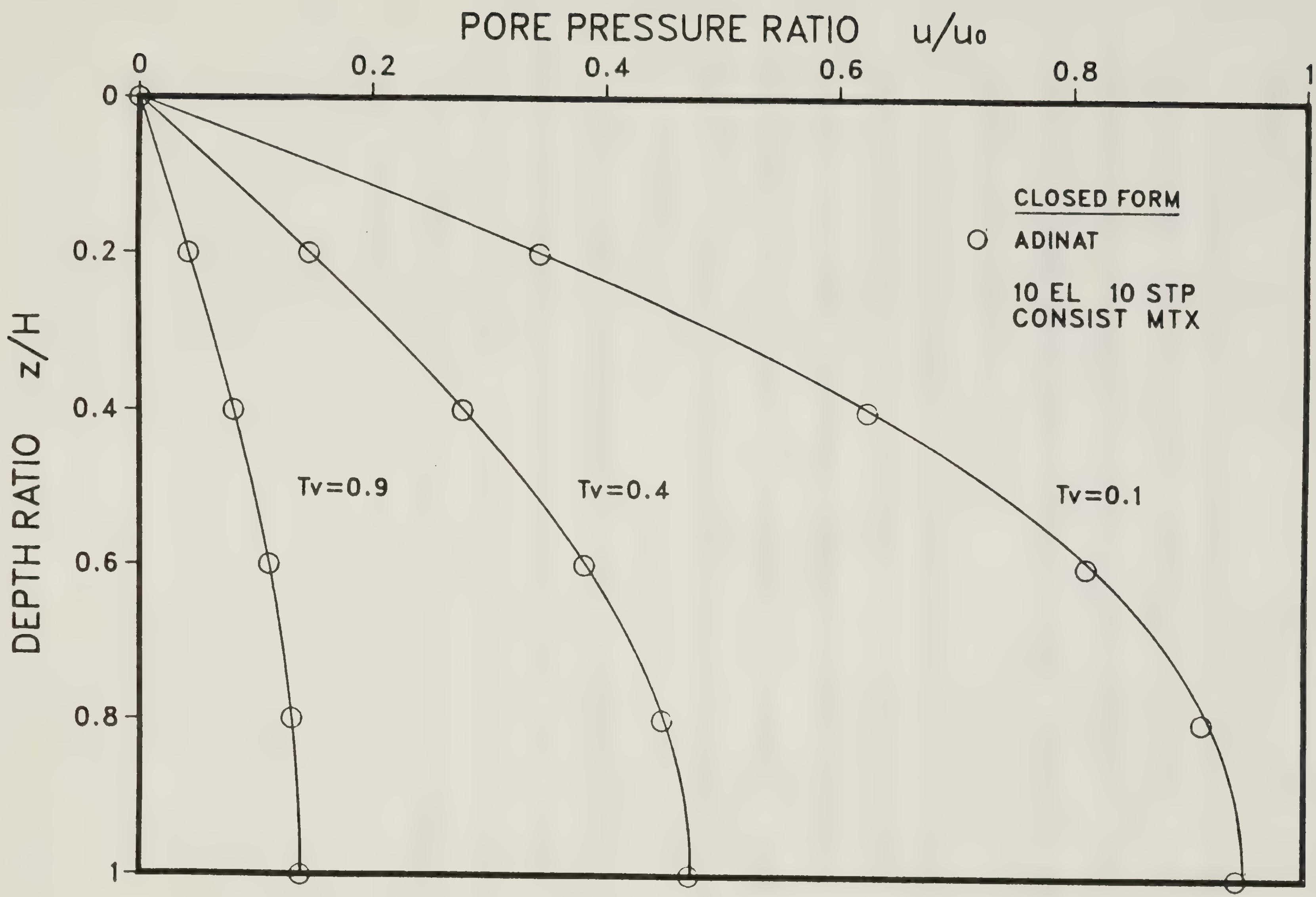


Figure 3.2 Excess pore pressure isochrones for half clay layer

code are assigned in the input. Only the pressure condition of the top node is ignored in singly drained layer.

b. The output values of excess pore pressure can be obtained for some selected time factors Tv by deliberately manipulating the input values of the total number of time steps and time interval, which product is the solution time t.

There are generally three approaches to obtain the required results. One of these is simply to solve for one Tv at a time. Several computer runs are then necessary for a range of required Tv values. This method will give a uniform degree of accuracy for all the results.

The other two methods are to solve for all the required time factors in a single run, with either only one or various time intervals. The degree of accuracy for the solutions, obviously, will not be consistent for these methods.

3.2 Homogeneous Layered Problems

3.2.1 General

In the previous section, the consolidation of a homogeneous soil stratum is considered. Stratified soil systems, however, are a common occurrence. Post glacial lake clays usually show laminated or layered structures, due to various sediments sizes during seasonal deposition. Problems of unlike soil layers are often encountered in earth dams, embankment buildings and landfills.

In this section, the consolidation of layered soils is discussed and examples are given. Since the material properties are assumed constant in each layer, the problems are not considered as *nonlinear*.

A closed-form solution for two layers is given by Gray (1945) and for multiple layers by Barden and Younan (1969), Schiffman and Stein (1970). Numerical solutions are suggested by Abbott (1960), Luscher (1965), Christie (1966), Davis and Lee (1969). Experimental studies are provided by Raymond (1966) and Barden and Younan (1969).

The governing equation, Eq 3.1, can be rewritten as

$$C_v^{i} \frac{\partial^2 u^{i}}{\partial z^2}(z,t) = \frac{\partial u^{i}}{\partial t}(z,t) \qquad (3.13)$$

where the superscript i refers to the i^{th} layer. The initial and boundary conditions are the same as in the preceding section. In addition to excess pore pressures, the continuity of flow between adjacent clay layers requires that flow velocities be equal at the common layer interfaces. These conditions are formulated as

$$u^{i}(z_i,t) = u^{i+1}(z_i,t) \qquad (3.14)$$

and

$$\left[k \frac{\partial u}{\partial z}(z_i,t) \right]_i = \left[k \frac{\partial u}{\partial z}(z_i,t) \right]_{i+1} \qquad (3.15)$$

where Z_i is the distance from the surface to the interface separating the ith and $(i+1)^{st}$ layer. The void ratio - effective stress relationship differs for each layer, as shown in Fig. 3.3.

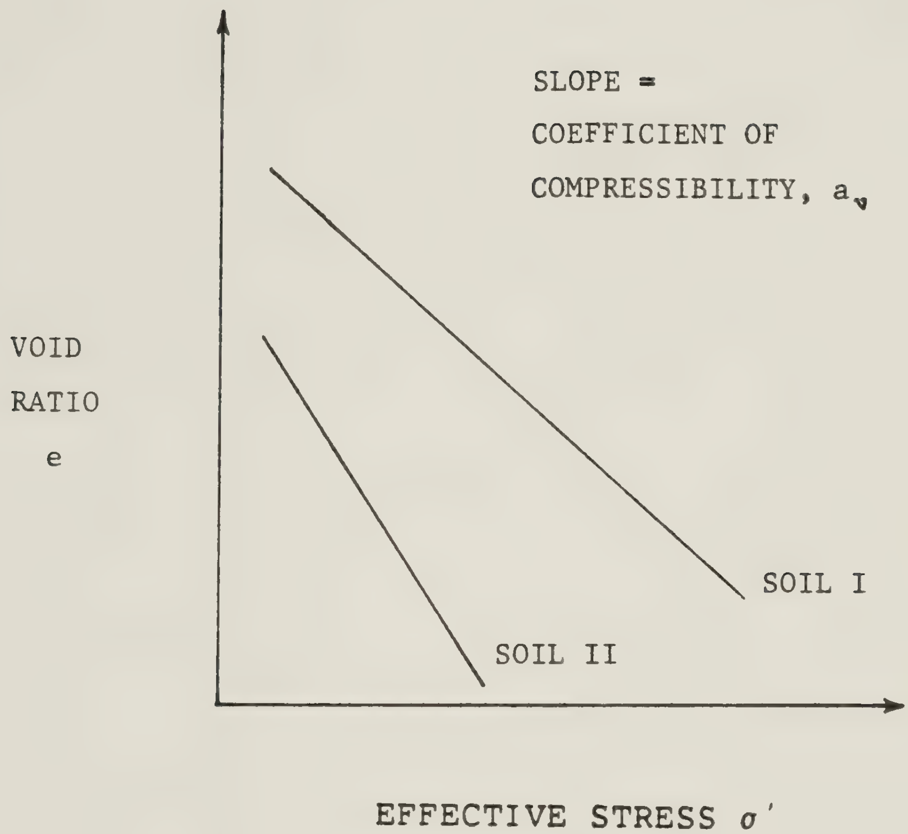


Figure 3.3 Void ratio - effective stress relationship in layered soils

Examples, consisting of two, three and four contiguous soil layers with singly or doubly drained boundaries, are analysed below. Conditions of uniform initial excess pore pressure and time-independent loadings are considered here. Closed-form, experimental or numerical results will also be included to compare with the ADINAT solutions.

3.2.2 Two Layers

Objective:

To verify ADINAT application to Gray's (1945) two layer consolidation problem.

Brief:

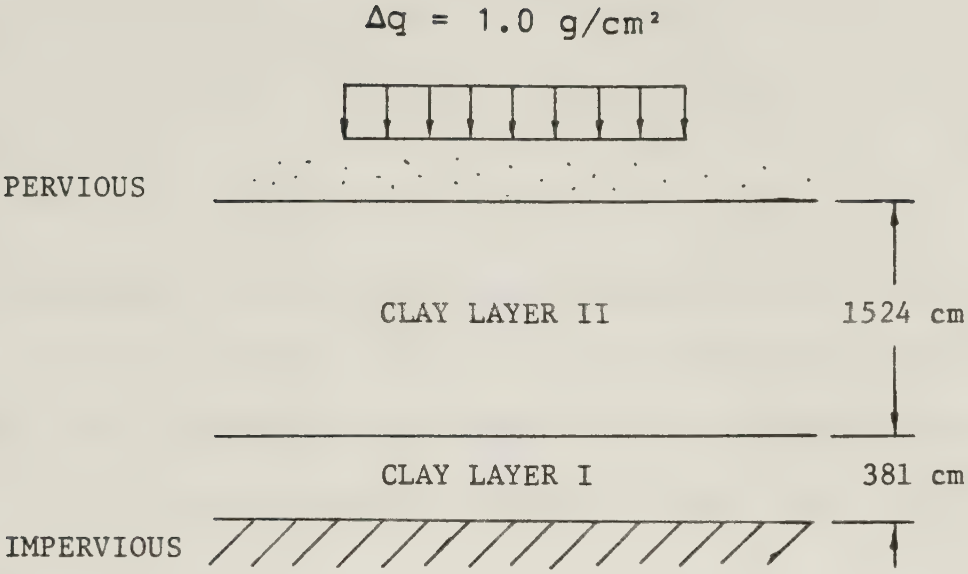
The first closed-form solution for a layered problem was published by Gray for two adjacent compressible strata. The impeded drainage condition was also considered in his paper.

Physical Problem:

Two adjoining layers of unlike compressible soils under a constant applied load are shown in Fig. 3.4. Boundary conditions and material properties are given in the figure.

Finite Element Model:

In the finite element model 20 equal length elements are applied for the clay stratum. Similar to the previous example, a consistent compressibility matrix option and



MATERIAL PROPERTIES:

LAYER I

k = 2.5×10^{-7} cm/sec

m_v = 8.0×10^{-5} cm²/g

Cv = 3.125×10^{-3} cm²/sec

LAYER II

k = 2.5×10^{-8} cm/sec

m_v = 2.0×10^{-4} cm²/g

Cv = 1.25×10^{-4} cm²/sec

FINITE ELEMENT MODEL FOR
THE TWO CLAY LAYERS

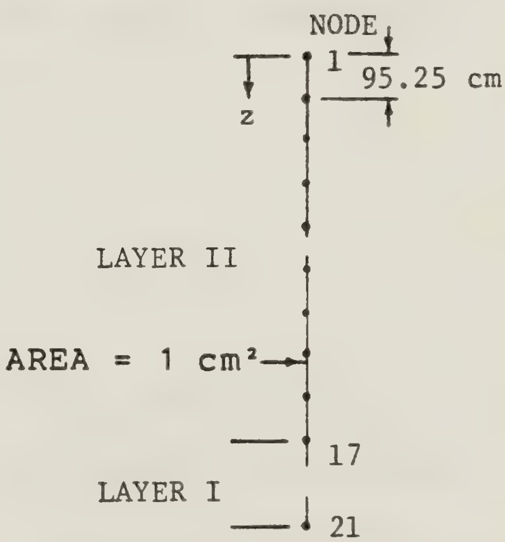


Figure 3.4 Consolidation analysis of two-layered problem

Euler backward method are chosen in the analysis.

Results:

The ADINAT results of excess pore pressure are plotted in Fig. 3.5 with Gray's solutions and close agreement is observed. The parameter Tb shown in the figure is the time factor for the bottom layer. ADINAT input data is given in Appendix A.2.

Others:

A Fortran program is used to compute the pore pressure according to Gray's formulation. The source code can be found in Appendix B.2.

User Hints:

Two approaches can be used for the data input in layered problems. The material properties for each layer can be input in ADINAT, either as different linear element groups in control card I, or as different sets of material properties in a single element group in control card X. The same results will be obtained for these two methods. Both input methods are used in the sample analyses and they can be seen from the datafiles in Appendix A.

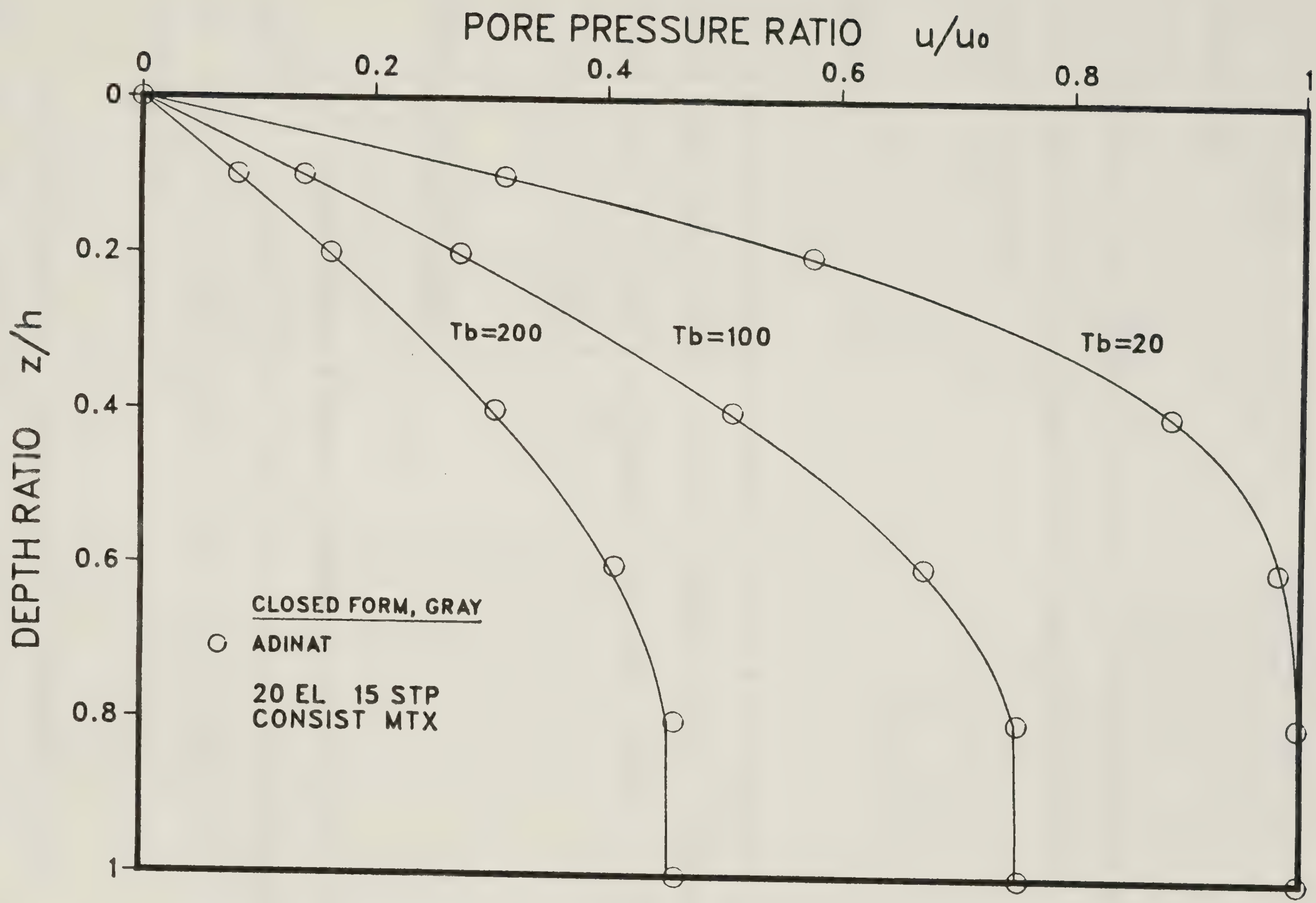


Figure 3.5 Pore pressure distribution for two-layered clay

3.2.3 Multiple-Layer System

Objective:

To verify the ADINAT analysis of the Barden and Younan (1969) solution of one dimensional consolidation for a three-layered soil.

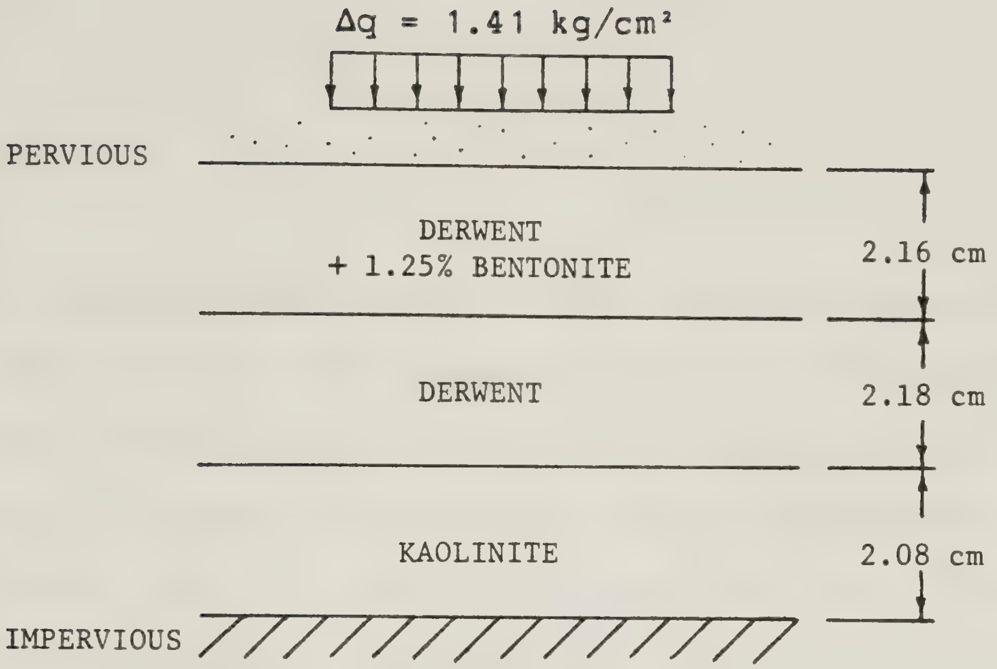
Brief:

Closed-form and experimental results are given by these authors for artifically prepared layered soils. The same problem here is also analysed by Desai and Johnson (1972) using a finite element scheme.

General Descriptions:

The singly drained three-layered soils and the applied loading are shown in Fig. 3.6. The material properties of each layer are given in the figure. Input data is in Appendix A.3.

The finite element model is also included in the Fig. 3.6. In order to be comparable with Desai and Johnson's (1972) results, eight elements are used for each



MATERIAL PROPERTIES:

LAYER	c_v (10^{4} cm²/yr)	k (cm/yr)
DERWENT + 1.25% BENTONITE	.716	.375
DERWENT	1.16	.546
KAOLINITE	7.01	3.14

FINITE ELEMENT MODEL FOR THE CLAY LAYER

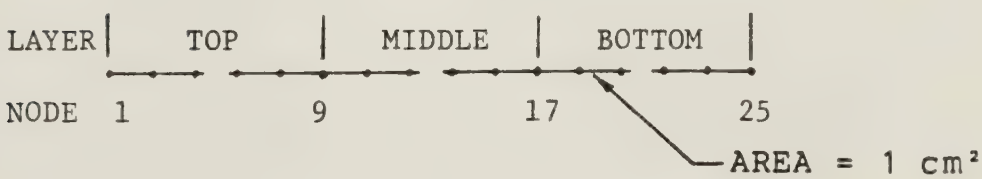


Figure 3.6 One dimensional consolidation analysis of a three-layered clay system

layer.

Results:

Pore pressure dissipation at the interface between Derwent and Kaolinite is plotted in Fig. 3.7. The ADINAT, closed-form, finite element (Desai and Johnson, 1972) and experimental results are compared. Good correspondence can be seen among the first three solutions over the entire range of consolidation, and with the experimental results above a time factor of about 20.

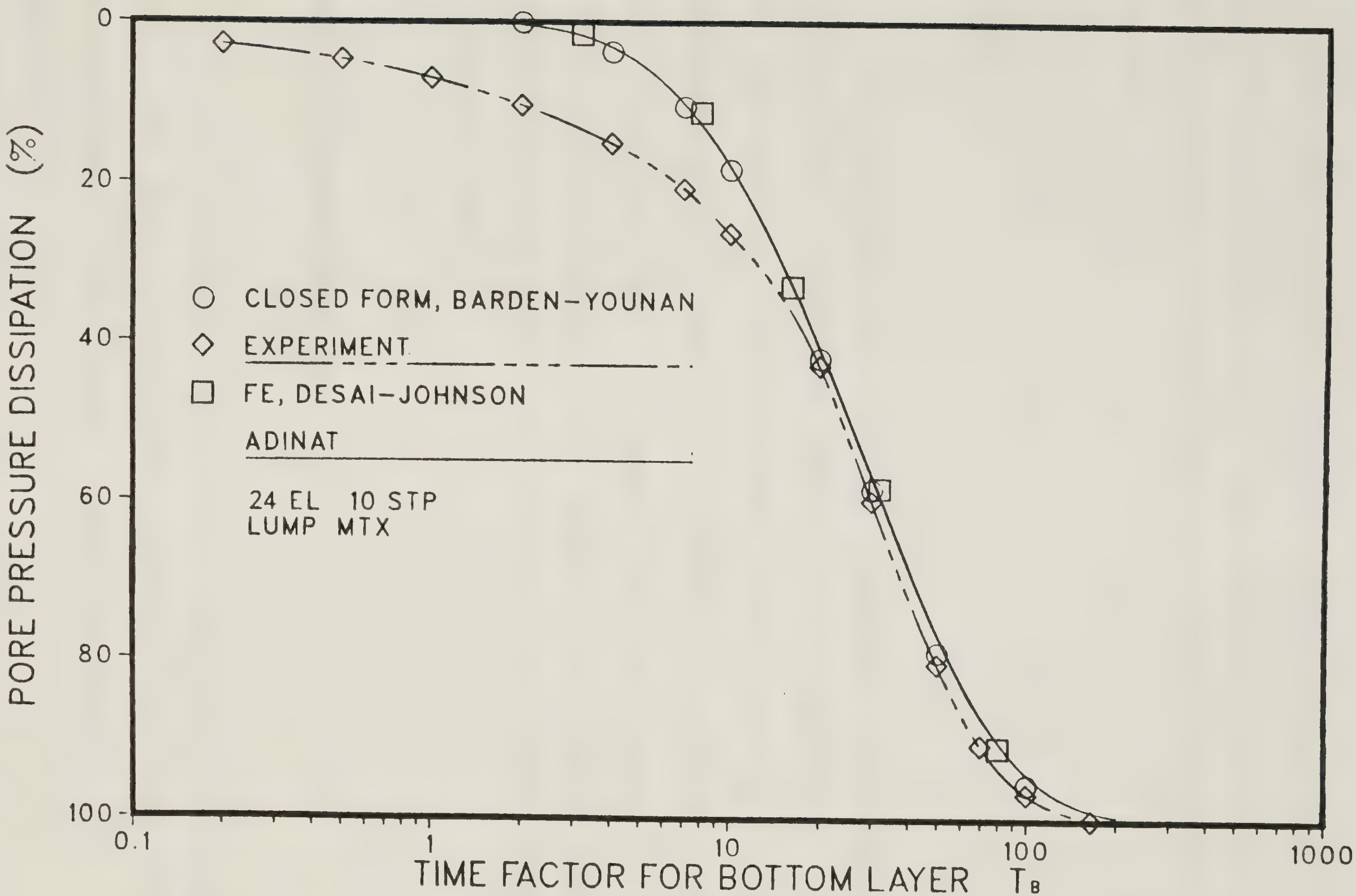


Figure 3.7 Pore pressure dissipation in three layers consolidation

Objective:

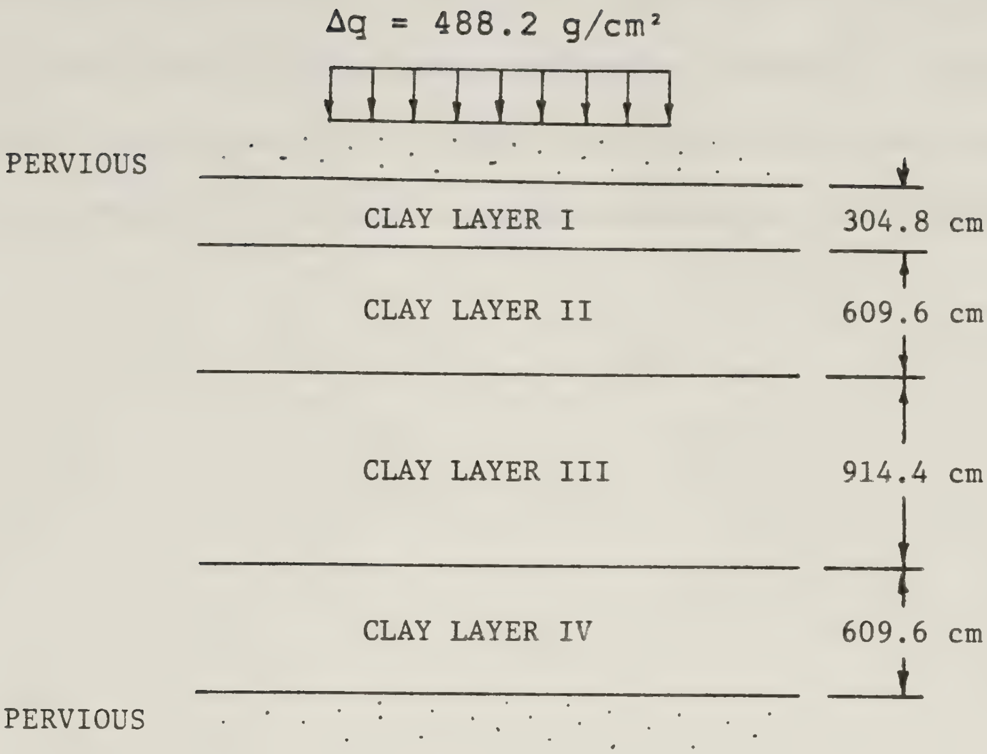
To verify ADINAT predictions in one dimensional consolidation analysis of a four contiguous layer soil system with the Schiffman and Stein (1970) closed-form solution.

Brief:

These authors have studied a multiple layer system with a general set of boundary conditions as impervious, impeded and free draining. Unrestricted loading history is also considered and a closed-form solution is provided using Fourier mathematics. An example of a four layer overconsolidated glacial till deposit with doubly drained boundaries and constant load is given. The same example is illustrated here.

Descriptions and Results:

Fig. 3.8 shows the soil profile and the finite element model. The material properties given by Schiffman and Stein are tabulated in the figure. Input datafile is in Appendix A.4.



MATERIAL PROPERTIES:

LAYER	C_v (10^{-4} cm²/sec)	m_v (10^{-6} cm²/g)	k (10^{-9} cm/sec)
I	4.42	6.29	2.78
II	20.6	3.99	8.26
III	5.89	1.99	1.17
IV	7.38	3.99	2.95

FINITE ELEMENT MODEL FOR THE WHOLE CLAY LAYER

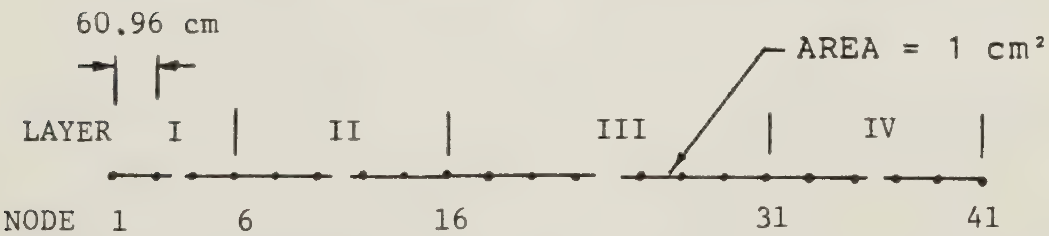


Figure 3.8 Consolidation analysis of a four-layered clay system

A set of excess pore pressure isochrones at 25%, 50% and 75% consolidation are computed using ADINAT. These results and the closed-form solutions from Schiffman and Stein are compared in Fig. 3.9, good agreement is observed.

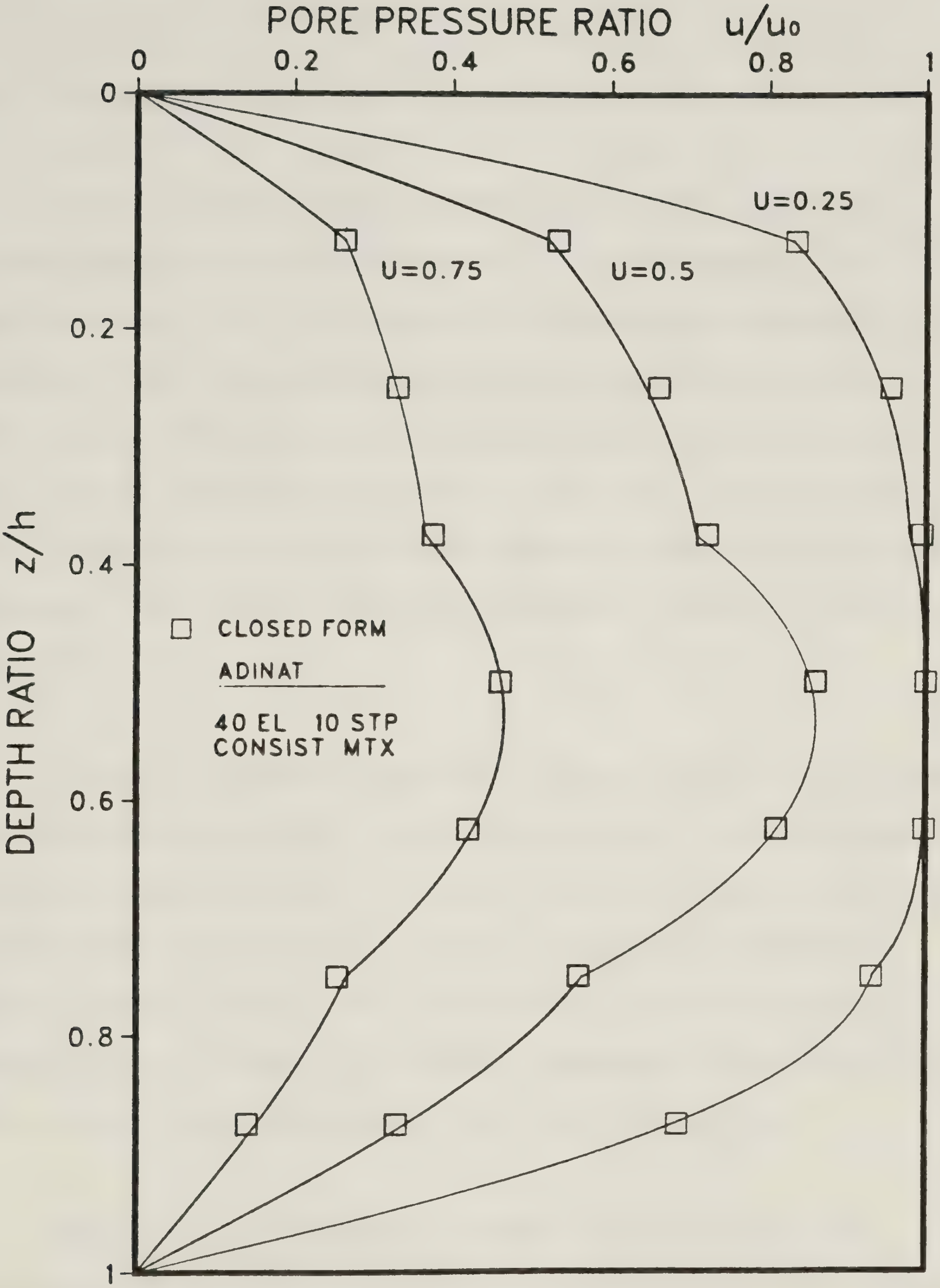


Figure 3.9 Pore pressure isochrones of a four-layered system

3.3 Continuous Spatial Variation of Material Properties

3.3.1 General

Another type of spatial variation, where the soil properties vary with depth in a continuous manner, is examined here. In this case, the strains are assumed to be so small that the permeability and compressibility are effectively independent of time but are continuous functions only of the space coordinate z. This type of problem is only a special case of the more general *material nonlinear* problem. The latter will be developed further in the next chapter.

Values of permeability and compressibility at any depth vary greatly due to the diverse soil type, initial stress state, stress increment and past stress history. The range of possible variations in nature is so wide that only special cases of distributions which can be expressed in special form are used in general analysis. Therefore, only these cases are discussed in the given examples.

These known functions, however, can be useful to simulate many real situations. A polynomial variation can be used to approximate the conditions in normally consolidated or overconsolidated clay layers with sufficient generality. For example, in the case of overconsolidated

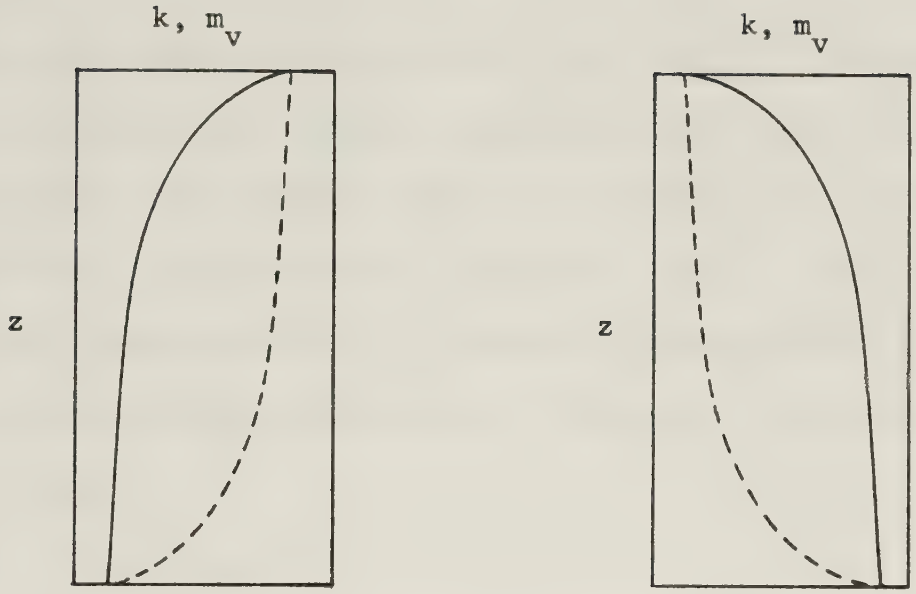
clay, where great amount of overburden has been eroded away in the geologic past, the upper layer usually is more permeable and compressible than at depth. This is illustrated in Fig. 3.10a.

Fig. 3.10b shows the variation in a normally consolidated clay layer. The low permeability and compressibility at top is due to surface drying and the development of a hardened crust. As shown in Fig. 3.10c and Fig. 3.10d, the sinusoidal distribution is close to the condition of partly consolidated clay layers, in which the center part is more or less permeable or compressible than the edges. Examples with these distributions will be analysed below.

The governing equation Eq. 3.1 of the conventional consolidation theory is extended to include spatial variations in the coefficient of permeability and the coefficient of volume compressibility as follows, (Schiffman and Gibson, 1964)

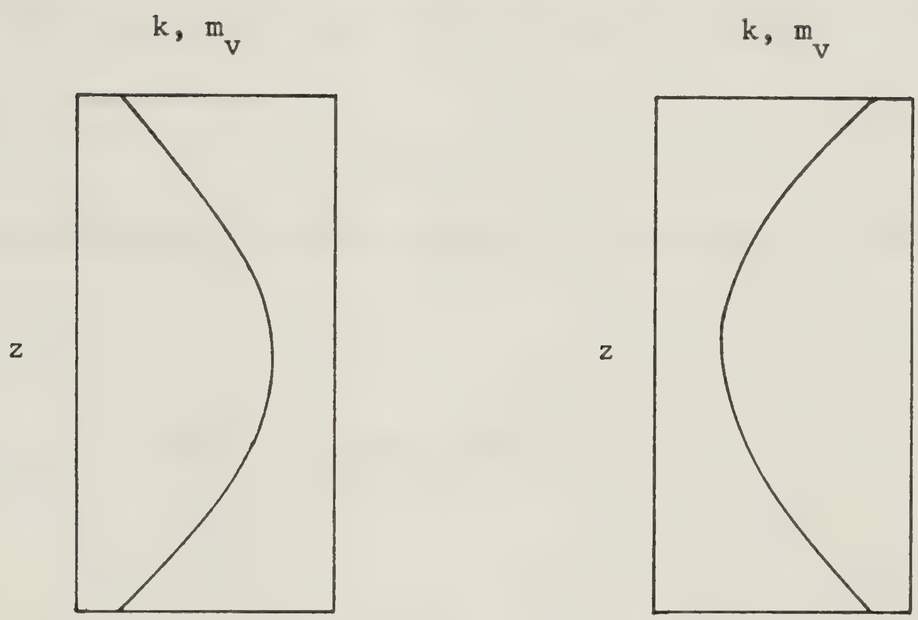
$$\frac{1}{\gamma_w} \frac{\partial}{\partial z}\{k(z)\frac{\partial u}{\partial z}(z,t)\} = m_v(z)\{\frac{\partial u}{\partial t}(z,t)\} \qquad (3.16)$$

The boundary and loading conditions are the same as in



(a) (b)

POLYNOMIAL VARIATION



(c) (d)

SINUSOIDAL VARIATION

Figure 3.10 Polynomial and sinusoidal functions for material properties distribution

Section 3.1.

Note that even if k(z) and $m_v(z)$ vary in the same manner and thus make Cv(z) a constant (see Eq. 3.7), Eq. 3.16 does not reduce to Eq. 3.1. This only takes place when k and m_v are separately constant. Eq. 3.16, however, is only an approximation to a general analysis of a thick layer with nonlinear properties. This will be discussed in the next chapter.

Note further that values of average consolidation for nonhomogeneous problems are determined from the settlement ratios. The same applies to nonlinear problems in the following chapters.

The polynomial relationship is expressed in the form of

$$KM(z) = KM_{\emptyset}(1+\eta z')^{\epsilon} \tag{3.17}$$

while the sinusoidal variations are given by

$$KM(z) = KM_{\emptyset} + A \cdot \sin(\pi z') \tag{3.18}$$

in which KM indicates either the permeability or compressibility, z' is the depth ratio z/h. The subscript ϕ denotes values at the top of the soil layer. The parameters ϵ and η describe the mode of variation of k and m_v. A is the amplitude of the sine function.

Published analytical solutions can only be found for a limited number of particular cases. Edelmann (1953) considered the linear variation in the modulus of elasticity and Martins (1965) has analysed the case of a linear variation in permeability. Closed-form solutions are provided for both cases. Schiffman and Gibson (1964) have considered a series of cases for the spatial variations in permeability and compressibility. Known distributions such as polynomial and sinusoidal functions are used in their analysis.

3.3.2 Variable Permeability with Constant Compressibility

Objective:

To verify ADINAT application to one dimensional consolidation with linear variation in permeability and contant compressibility.

Brief:

Martins (1965) studied the special case of linear permeability and constant compressibility. He assumed $\epsilon=1$ in Eq. 3.17 for compressibility and use a polar coordinate transformation of Eq. 3.16, which becomes

$$\chi\{\frac{1}{r}\cdot\frac{\partial u}{\partial r}(r,t) + \frac{\partial^2 u}{\partial r^2}(r,t)\} = \frac{\partial u}{\partial t}(r,t) \tag{3.19}$$

where

$$\chi = k_\emptyset \, \eta^2/(4 \, \gamma_w \, h^2 \, m_v) \tag{3.20}$$

and

$$r = (1 + \eta z')^{1/2} \tag{3.21}$$

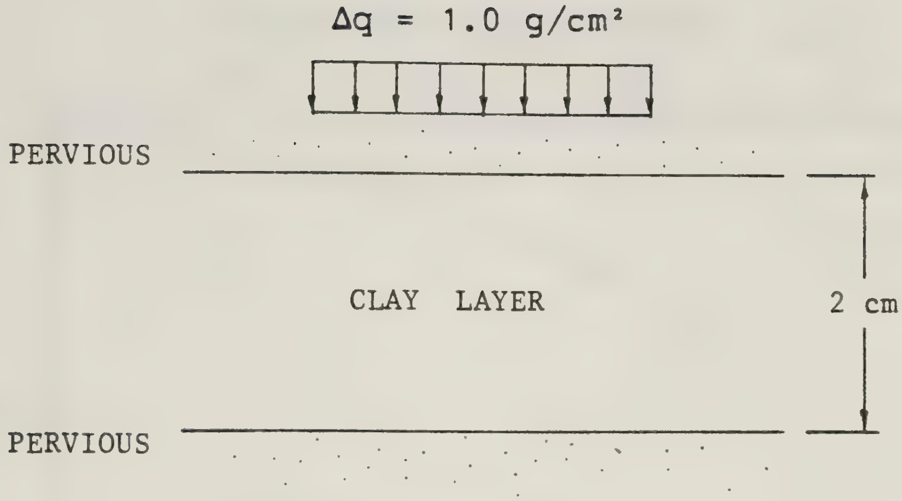
$k_\emptyset$ is the value of the coefficient of permeability at the layer surface. This equation can be considered as the diffusion equation of an infinite cyclinder with radial flow and constant diffusivity, where Carslaw and Jaeger's (1959) solution is then applied.

General Description:

Fig. 3.11 shows the soil profile and the boundary conditions of the problem. The material properties and finite element model are given in the figure. Consistent compressibility matrix computation and Euler backward method are used. Datafile is included in Appendix A.5.

Results:

The pore pressure isochrone predicted by ADINAT at 50% consolidation is given in Fig. 3.12, and compared with Martins' closed-form solution. Good agreement is shown. The maximun discrepancy is about 4% at the bottom part of the curve.

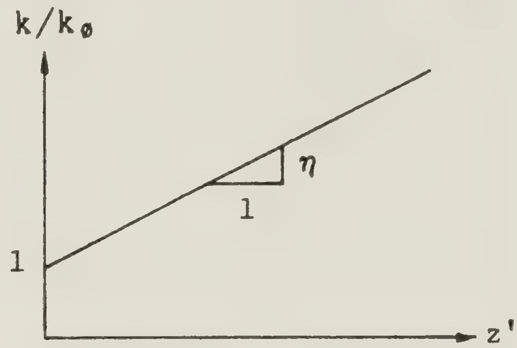


PERMEABILITY MODEL:

$k = k_{\emptyset}(1 + \eta z')$

$k_{\emptyset} = 1 \times 10^{-5}$ cm/sec

$\eta = 15.0$



MATERIAL PROPERTIES: $m_v = 1.0$ cm²/g

$\gamma_w = 1.0$ g/cm³

FINITE ELEMENT MODEL FOR THE CLAY LAYER

40 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 3.11 One dimensional consolidation analysis with linear variation in permeability

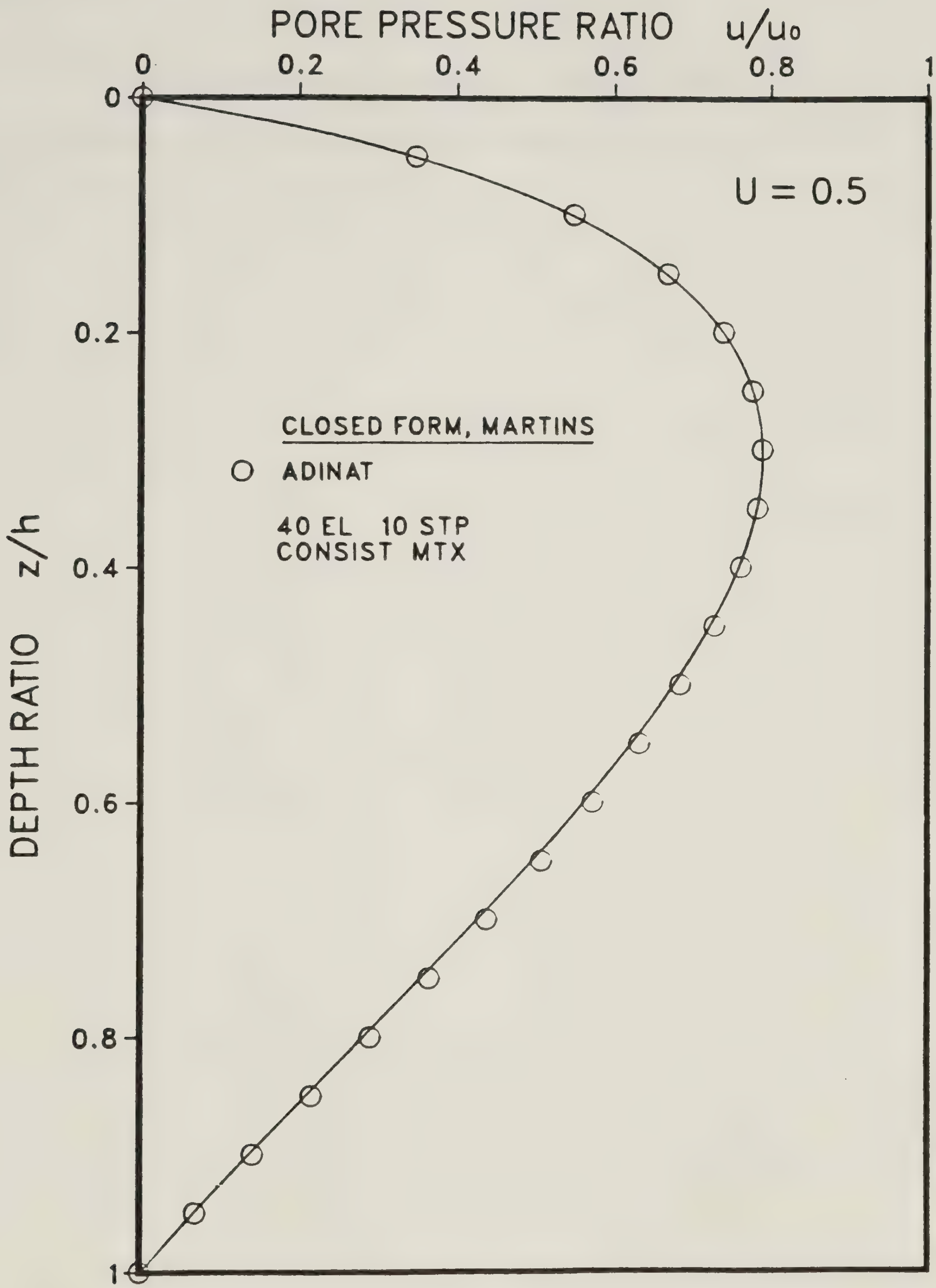


Figure 3.12 Pore pressure isochrones: linear variation in permeability

Remarks:

A Fortran program is used to compute Martins' formulation. A listing of the source code is included in Appendix B.3.

Objective:

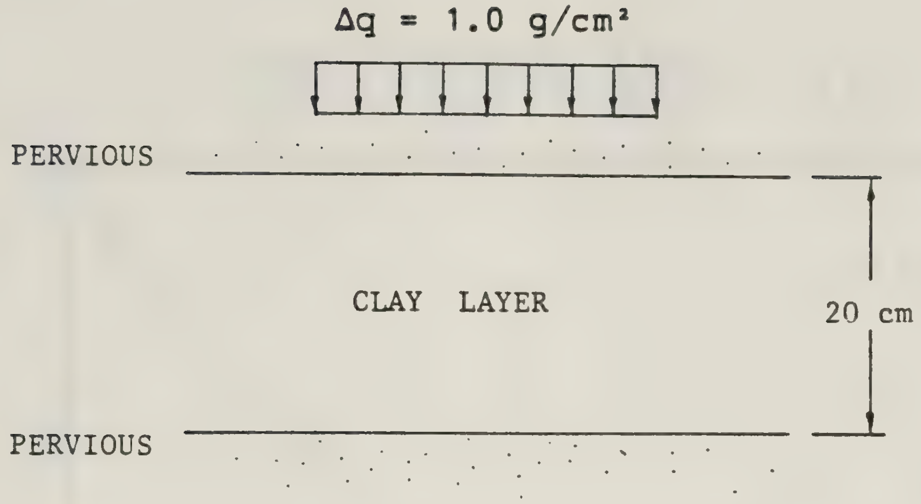
To show ADINAT analysis of one dimensional consolidation with polynomial distribution in permeability and constant compressibility.

General Description:

Eq. 3.16 and 3.17 are applied in the analysis. The parameters ϵ and η estimated from Schiffman and Gibson (1964) are used. Fig. 3.13 shows the soil profile and the finite element model. Forty equally spaced one dimensional elements will be used for the clay layer. Euler backward method and lumped compressibility matrix are utilized in the computation. The ADINAT input data is given in Appendix A.6

Results:

The ADINAT output of excess pore pressure at 50% consolidation is compared with the solution of Schiffman and Gibson and presented in Fig. 3.14. Good correspondence is observed.



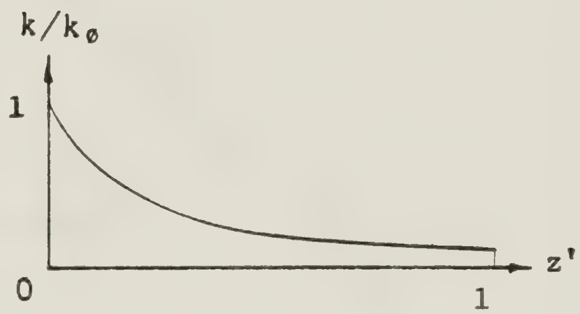
PERMEABILITY MODEL:

$k = k_{\emptyset}(1 + \eta z')^{\epsilon}$

$k_{\emptyset} = 1.0$ cm/sec

$\eta = 8.0$

$\epsilon \simeq -1.05$



MATERIAL PROPERTIES: $m_v = 1.0$ cm²/g

$\gamma_w = 1.0$ g/cm³

FINITE ELEMENT MODEL FOR THE CLAY LAYER

40 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 3.13 One dimensional consolidation analysis with polynomial variation in permeability

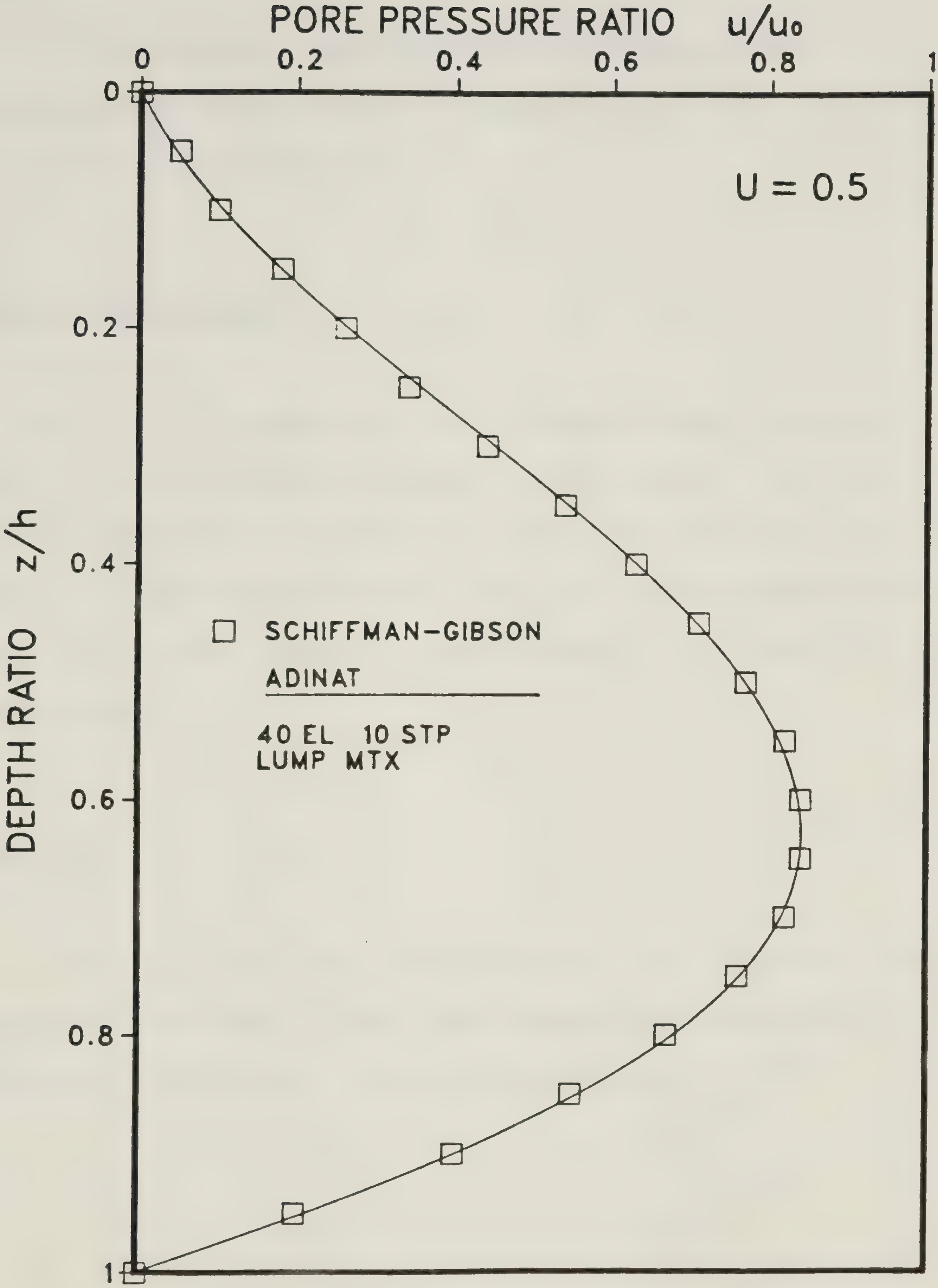


Figure 3.14 Pore pressure isochrones: polynomial variation in permeability

Objective:

To show ADINAT application to one dimensional consolidation with constant compressibility and sinusoidal variation in permeability.

General Description:

Eq. 3.18 is employed with the amplitude A obtained from Fig. 13 in Schiffman and Gibson (1964) paper. The soil profile and material properties are given in Fig. 3.15. The finite element model and the time integration method are the same as the last example. ADINAT datafile is shown in Appendix A.7.

Results:

Fig. 3.16 shows the comparison of the resulting pore pressure isochrone at 50% consolidation and the solution by Schiffman and Gibson. Good correspondence is noted.

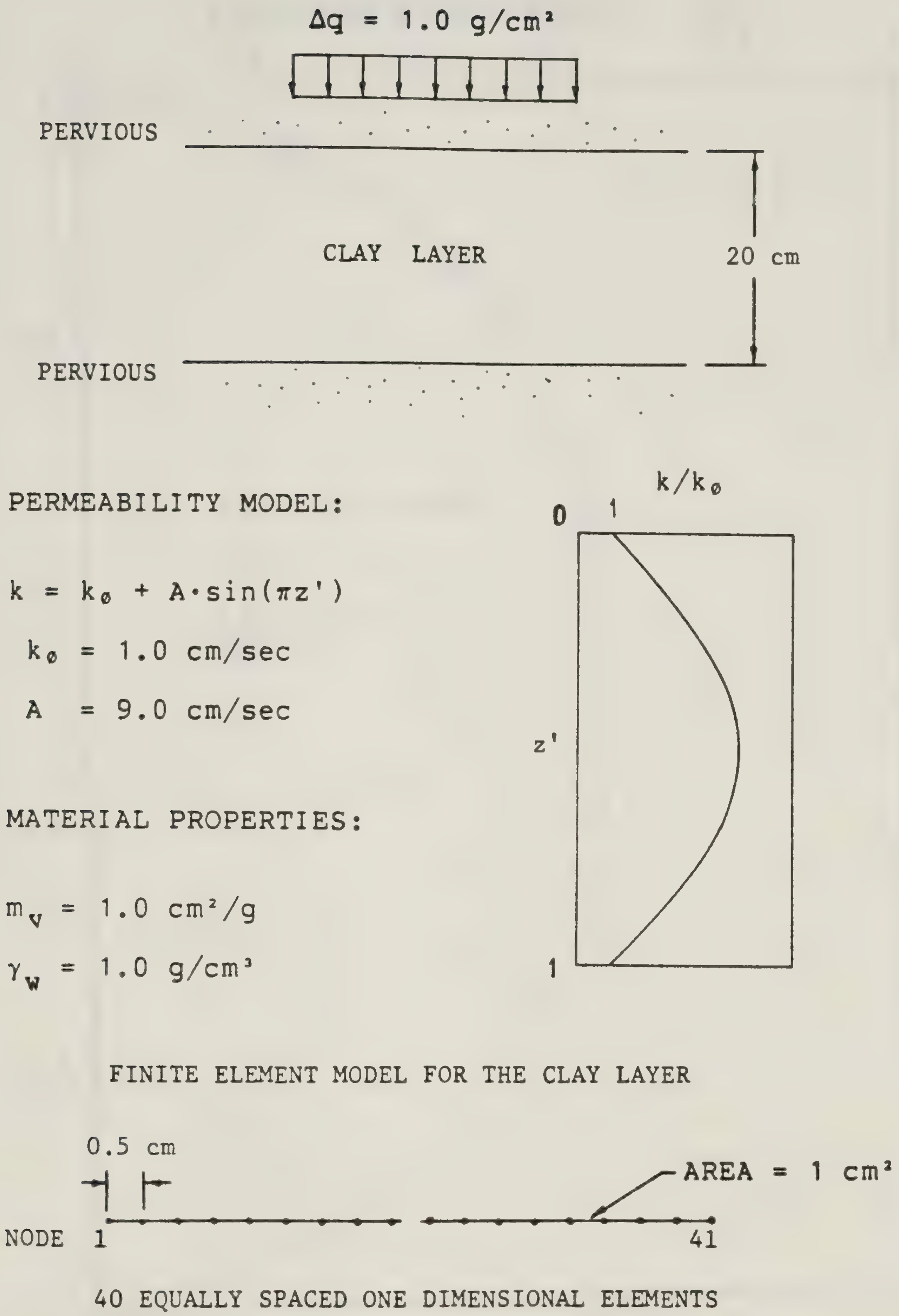


Figure 3.15 One dimensional consolidation analysis with sinusoidal variation in permeability

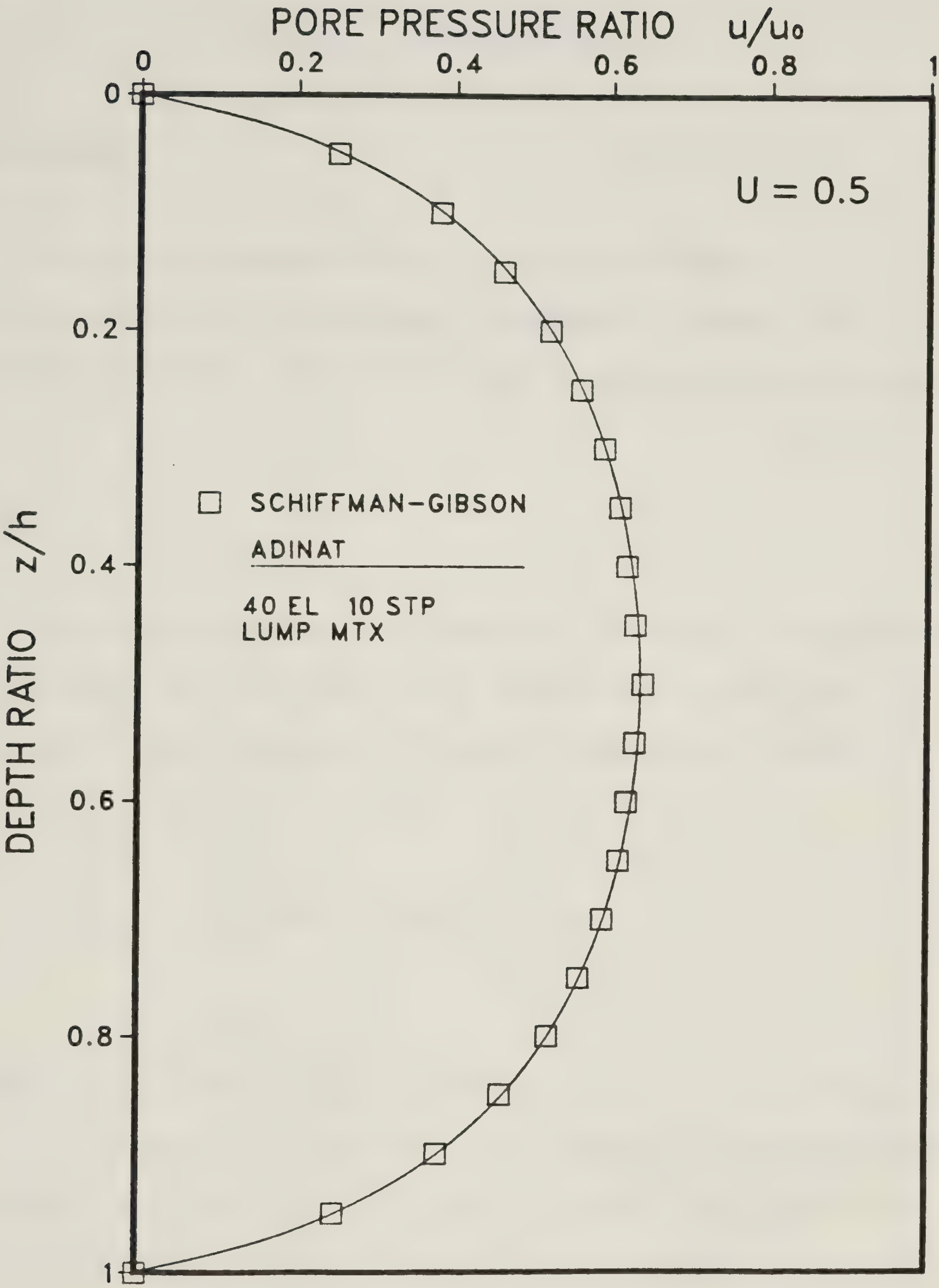


Figure 3.16 Pore pressure isochrones: sinusoidal variation in permeability

3.3.3 Variable Compressibility with Constant Permeability

Objective:

To verify ADINAT analysis of the variable compressibiltity and constant permeability model with Edelmann's (1953) solution in one dimensional consolidation.

Brief:

Edelmann assumed the linear variation of the modulus of elasticity, E, in a soil layer whence the coefficient of compressibility becomes a rational function of depth,

$$m_v(z) = 1/(c'\gamma_t z + \sigma'_\emptyset) \tag{3.22}$$

where $\sigma'_\emptyset$ is a small initial effective stress at surface and c' is a constant characterize the manner of variation of E. Putting this into Eq. 3.16, which can be simplified into a different form

$$\frac{\partial^2 u}{\partial z^2}(z,t) = \frac{1}{z+\eta}\cdot\frac{\partial u}{\partial T_1}(z,t) \qquad (3.23)$$

where

$$\eta = \sigma'_{\phi} \,/\, (c' \;\gamma_t) \qquad (3.24)$$

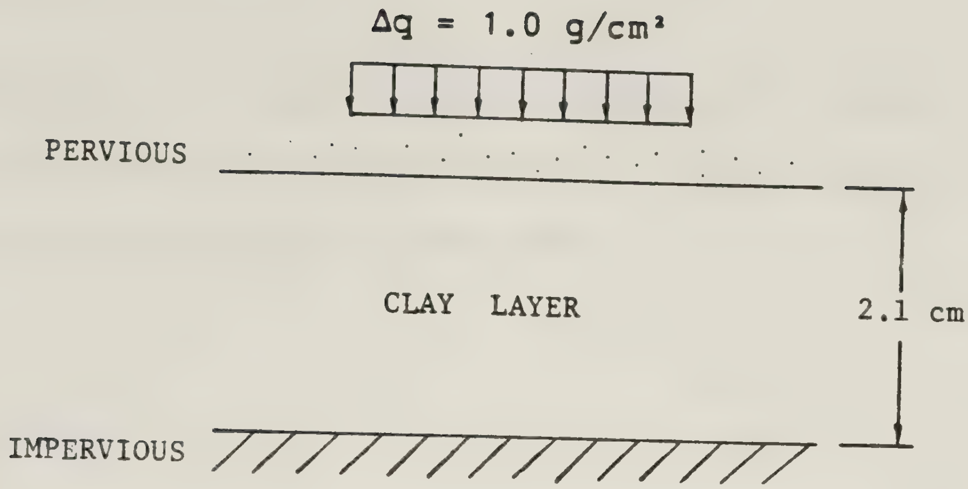
and

$$T_1 = (c' \; k \; \gamma_t \; t) \,/\, \gamma_w \qquad (3.25)$$

Edelmann employed Fourier mathematics to obtain a closed-form solution for the case of a single layer with only top drainage.

Description of Problem:

The singly drained soil profile and loading are presented in Fig. 3.17. The compressibility model and material properties are given in the figure. The ADINAT datafile is given in Appendix A.8.

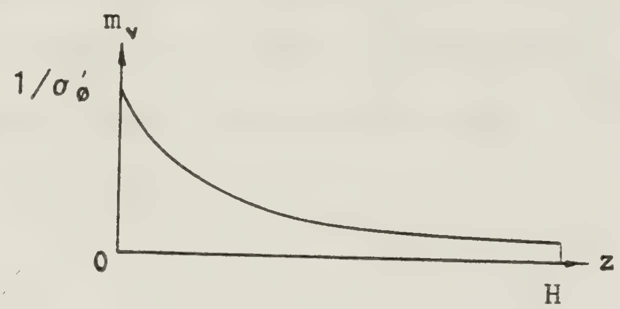


COMPRESSIBILITY MODEL:

$$m_v = \frac{1}{c'\gamma_t z + \sigma'_\phi}$$

$c' = 15$

$\sigma'_\phi = 6\ g/cm^2$



MATERIAL PROPERTIES:

$k = 1 \times 10^{-5}$ cm/sec

$\gamma_t = 1.0\ g/cm^3$

$\gamma_w = 1.0\ g/cm^3$

FINITE ELEMENT MODEL FOR THE CLAY LAYER

40 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 3.17 One dimensional consolidation analysis with variable compressibility

Finite Element Model:

The finite element model consists of 40 equally spaced elements. Consistent compressibility matrix option and Euler backward method is employed.

Results:

Edelmann's closed-form solution at 50% consolidation is compared with the ADINAT pore pressure results in Fig. 3.18 and good agreement is shown. Maximum error of the pore pressure ratio occurs at the top part of the plot and is in the order of 10^{-2}.

Remarks:

A Fortran IV program is prepared for Edelmann's solution. The roots for the Bessel functions in the calculation can be found from Abramowitz and Stegun (1972). The required time for the analysis is computed by the program. A listing of the source code is included in Appendix B.4.

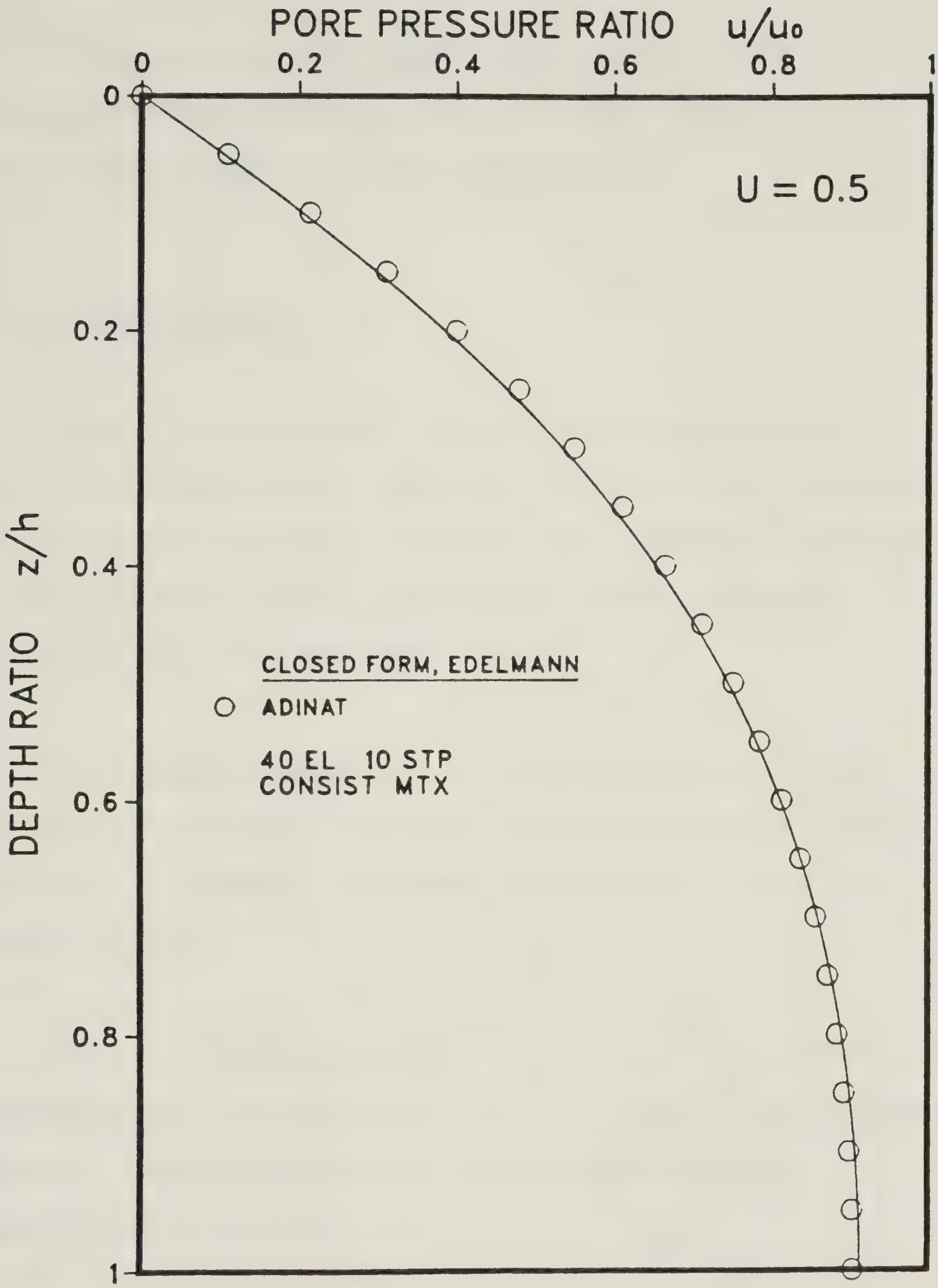


Figure 3.18 Pore pressure isochrones: variable compressibility

Objective:

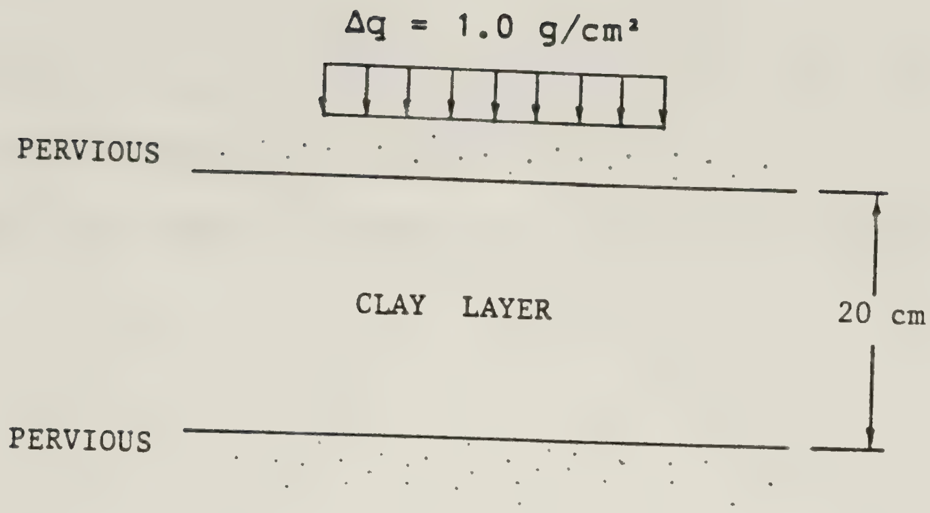
To demonstrate the ADINAT application in one dimensional consolidation with sinusoidal variation in compressibility and constant permeability.

General Description:

The soil profile and loading for the problem is described in Fig. 3.19. With the values ϵ and η estimated from Schiffman and Gibson (1964), the compressibility model is obtained and given in the figure. Other material properties are also included.

The required time in the analysis is estimated by Simpson's rule in the numerical integration of the average settlement. A sample of ADINAT input data is given in Appendix A.9.

The finite element model, time integration method and compressibility matrix option are the same as the previous example. These can also be found in the datafile in Appendix A.9.

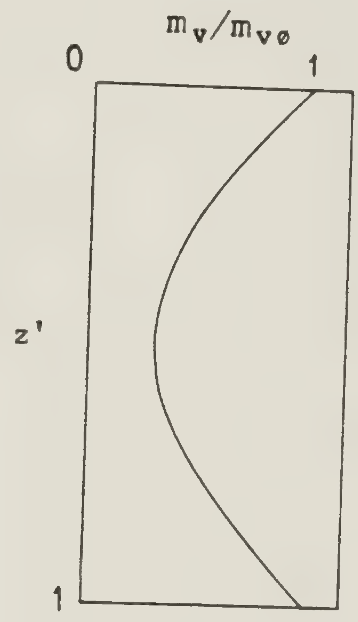


COMPRESSIBILITY MODEL:

$m_v = m_{v\phi} - A \cdot \sin(\pi z')$

$m_{v\phi} = 1.0$ cm²/g

$A = 0.9$ cm²/g



MATERIAL PROPERTIES:

$k = 1.0$ cm²/sec

$\gamma_w = 1.0$ g/cm³

FINITE ELEMENT MODEL FOR THE CLAY LAYER

40 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 3.19 One dimensional consolidation analysis with sinusoidal variation in compressibility

Results:

The excess pore pressure isochrone at 50% consolidation predicted by ADINAT is compared with the solution by Schiffman and Gibson in Fig. 3.20, and close agreement is found.

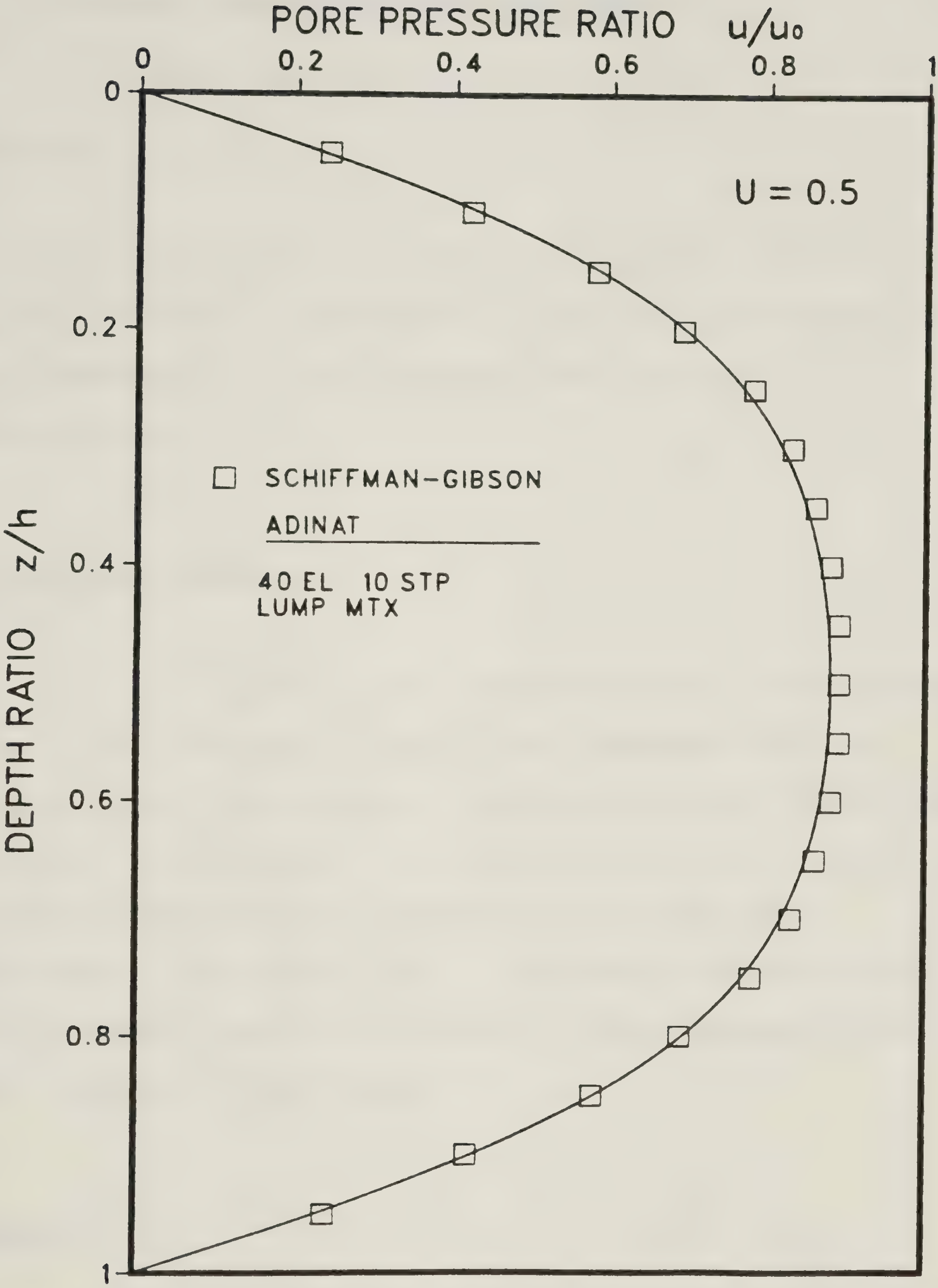


Figure 3.20 Pore pressure isochrones: sinusoidal variation in compressibility

3.3.4 Geometric Variation of Material Properties with Constant Coefficient of Consolidation

Objective:

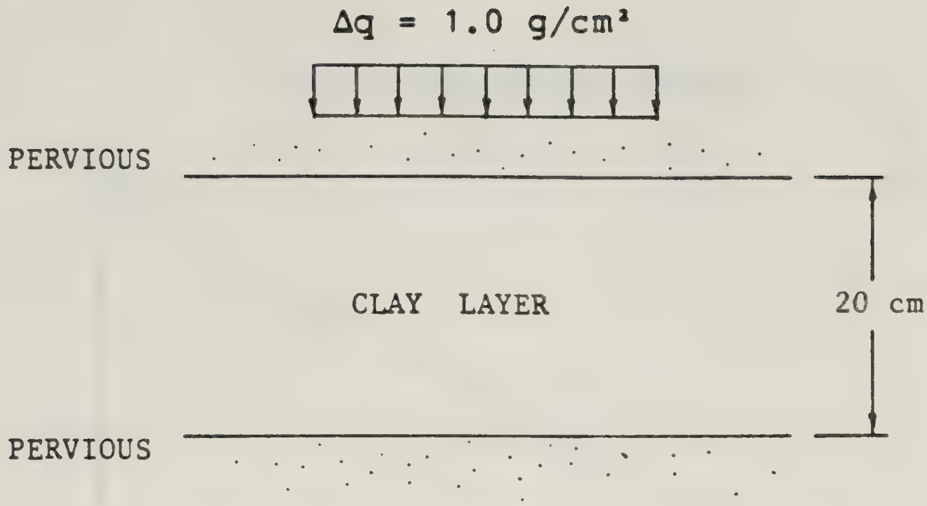
To illustrate the application of ADINAT in the analysis of one dimensional consolidation with variable permeability and compressibility but constant coefficient of consolidation.

General Description:

Fig. 3.21 gives the soil profile and the finite element model. The estimated values of the parameters for the material model are obtained from Schiffman and Gibson (1964) and given in the figure. The estimated time is found from Simpson's rule for the integration of the average settlement. The ADINAT data is included in Appendix A.10. Finite element model is the same as previous example and is also included in the figure.

Results:

The pore pressure predicted by ADINAT is presented in Fig. 3.22. This same problem is also analysed by Schiffman and Gibson (1964), close approximation is shown.



MATERIAL MODEL:

$$k = k_{\emptyset}(1 + \eta z')^{\epsilon}$$

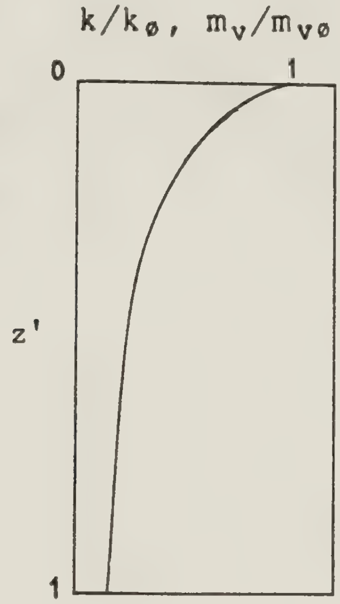
$$m_v = m_{v\emptyset}(1 + \eta z')^{\epsilon}$$

$k_{\emptyset}$ = 1.0 cm/sec

$m_{v\emptyset}$ = 1.0 cm²/g

η = 8

$\epsilon \simeq -1.05$



OTHER MATERIAL PROPERTIES: γ_w = 1.0 g/cm³

C_v = 1.0 cm²/sec

FINITE ELEMENT MODEL FOR THE CLAY LAYER

40 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 3.21 One dimensional consolidation analysis with polynomial distribution in material properties

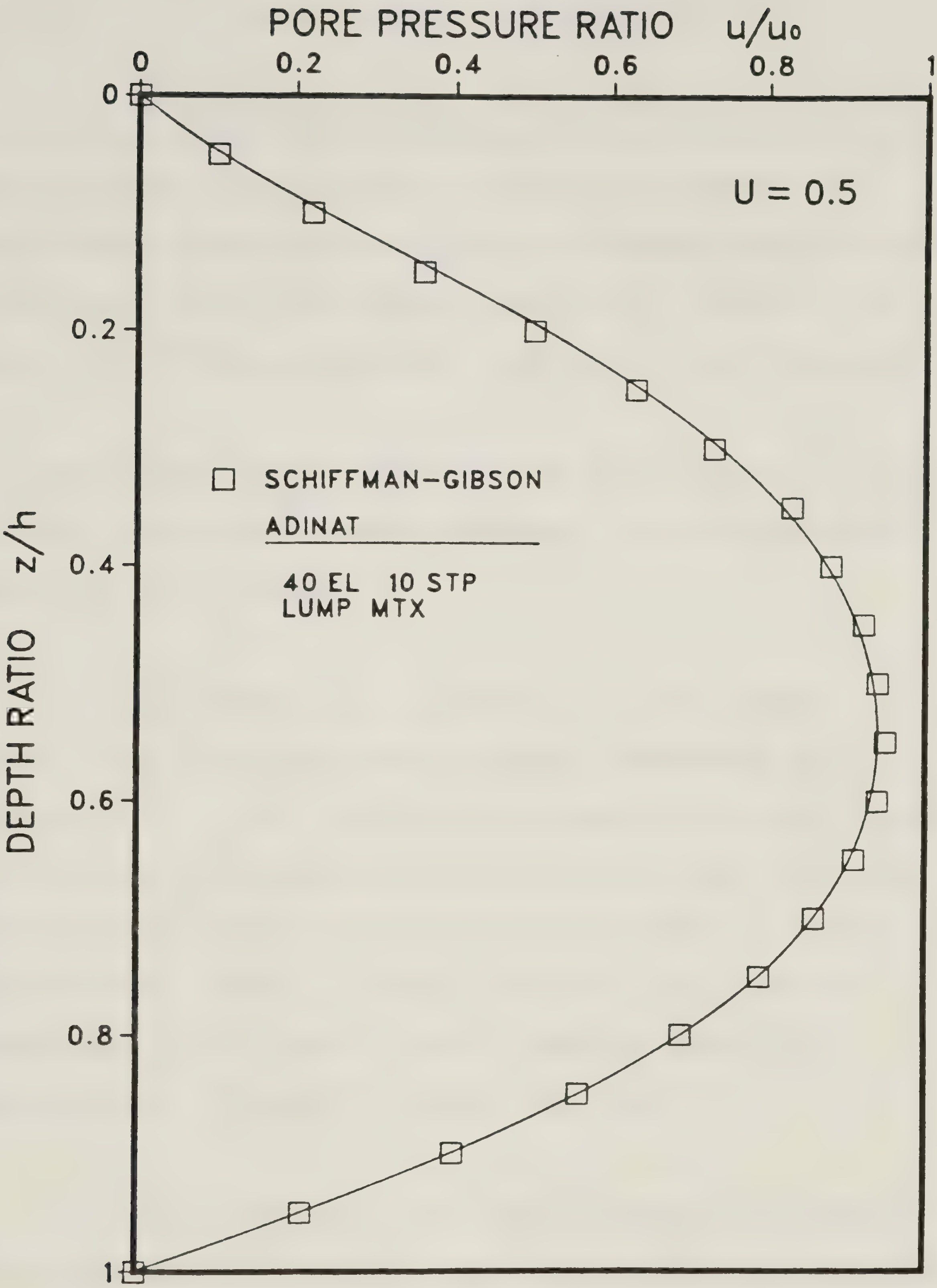


Figure 3.22 Pore pressure isochrones: variable permeability & compressibility with constant coefficient of consolidation

3.4 Discussion

In most of the above examples, closed-form solutions are given for a qualitative evaluation of ADINAT predictions. The high accuracy of the ADINAT results found in the examples in this chapter serves as a check on the reliability of the program when applied to such analyses.

The average cost of each run is about thirty to fifty cents for the size of above problems. This indicates the economy in using ADINAT.

Since the excess pore pressure u is the primary unknown, the finite element procedure guarantees the continuity of u, but not the pore pressure gradient, $\partial u/\partial z$. The continuity requirement in layered problems, Eq. 3.15, is therefore not strictly satisfied for the case of linear finite element model in ADINAT. However, the accurate predictions in the above layered examples assure the applicability of ADINAT in these analyses.

For layered problems with severe changes in material properties, however, higher-order finite element model may become necessary. A further discussion on this subject can be found in Desai and Johnson (1972).

For the analyses in this chapter, pore pressure results are obtained directly from the program output. Subroutines or supplemental programs may be then required for the computation of other quantities such as average pressure dissipation or settlement. The settlement ratio becomes a more important measure for comparisons in nonlinear problems.

4. GENERAL STUDY OF ADINAT APPLICATION IN NONLINEAR CONSOLIDATION

Nonlinear consolidation theories have been developed for decades and numerous studies can be found. The scope of discussions in this and subsequent chapters are in accordance with the first seven assumptions given in Section 3.1.1.

Published nonlinear theories are reviewed first. The general governing equation is then derived, in order to facilitate the discussions that follows. It will be shown to embrace most nonlinear theories previously cited.

From this equation, different formulations with the common major simplifications will be generated. They will be presented in a form suitable for use with ADINAT. These formulations form the basis for the numerical treatment of various nonlinear theories using the program. Applications of these *ADINAT equations* to existing theories will be illustrated in subsequent chapters.

4.1 Review of Nonlinear Consolidation Theories

For many years, attempts have been made by researchers to modify the assumptions implicit in Terzaghi's theory to agree more closely with the physical conditions and material properties in real soils. The changes of permeability and compressibility in a mass of real soil are two significant departures from Terzaghi's classical theory, which result in a nonlinear theory.

The first attempt to deal with these nonlinearities was by Schiffman and Gibson (1964), as illustrated in Section 3.3, where they considered the material properties as spatially dependent. Since the effective stress also varies with depth, the nonlinear behavior is then treated as a geometric nonhomogeneous problem. This, however, is only an approximate approach to the nonlinear stress - strain and stress - permeability behavior.

Permeability is known to vary with effective stress in a complicated manner. A widely used law is the linear relationship between the void ratio and logarithm of permeability. Raymond (1966 & 1969), Poskitt (1969), Poskitt and Birdsall (1971), Berry and Poskitt (1972) have used this relation in their theories. Other relationships are also proposed by Schmid (1957), Barden and Berry (1965),

Hwang (1966), Samarasinghe *et al* (1982), Juarez-Badillo (1983). Schiffman (1958) and Koppula (1970) are special cases of above.

For the stress range normally encountered in practice, the usually accepted compressibility law is the linear relationship between void ratio and logarithm of vertical effective stress. Barden and Berry (1965), Davis and Raymond (1965), Mikasa (1965), Raymond (1966), Poskitt (1969), Wilson and Hwang (1969), all used this relation in developing their analyses.

It is found in some soils that the coefficient of consolidation varies much less than either the permeability or the compressibility. Researchers such as Janbu (1965), Davis and Raymond (1965), Mikasa (1965), Davis (1971) assume this cofficient to be a constant in their formulations. The assumptions of constant coefficient of consolidation and the logarithmic effective stress - void ratio relation have also been shown from laboratory tests for normally consolidated clay, and where the secondary effect is ideally absent.

Many of these theories, such as Barden and Berry (1965), Davis and Raymond (1965), Raymond (1966), have introduced nonlinear behaviour in thin layered soils although the restraint of small strain still persists.

Small strain analysis is based on the assumption that the deformation is small compared to the thickness of the consolidating layer. Therefore, it is not appropriate for an extremely compressible soil and only applicable to oedometer tests or soil samples sufficiently thin that self-weight effects can be neglected.

The usual coordinate system employed in small strain theory is the Eulerian system where all measurements are referenced in space to a fixed datum. Settlement computation based on small strain theory, therefore, may probably be in error since the movement of boundaries is assumed in a fixed coordinate system.

Finite strain analyses for thin layers have been developed by McNabb (1960), Mikasa (1965), Gibson *et al* (1967), Poskitt (1969), Wilson and Hwang (1969), Mesri and Rockhsar (1974), Lee and Sills (1979). The first presents the fundamental nonlinear equations without providing any solution, while the last uses a moving boundary approach to account for large strains. Mikasa assumed a constant coefficient of consolidation and used the compression strain as the primary unknown in his governing equation. Settlement analysis is given by Wilson and Hwang for different load ratios and permeability parameters. Mesri and Rockhsar have carried out an extensive study of nonlinear behavior, but failed to account for the influence

of soil depth.

The general theory formulated by Gibson *et al* (1967) reduced many limitations in the conventional analysis. It represents a basis for various future researchers. Studies using thin layer approximation have been made by these authors and other researchers. Their original equation with logarithmic material laws and further assumptions is solved analytically by Poskitt (1969) using a perturbation method. A closed-form solution is found by Simons and Beng (1969) with other approximations. Comparison with experimental results is presented by Burland and Roscoe (1969).

Experimental investigation and numerical solution of Gibson *et al*'s (1967) general formulation is suggested by Monte and Krizek (1976). In their analysis, the liquid limit state is taken as the datumn for strain measurement. Linear relationship between constrained modulus and strain is employed, and the permeability is expressed as a second degree function of void ratio.

In engineering projects such as large embankments, reclamation filling and groundwater lowering, very deep and soft clay layers may be involved. Large settlements may occur and effects of self-weight cannot be ignored.

Raymond (1969) and Davis (1971) have considered effects of layer depth in the context of small strain. Numerical solutions for Davis (1971) is suggested by Viggiani (1973). Variable load increment is also considered by Raymond (1969) and Viggiani (1973).

Studies accounting for both the finite strain and self-weight effect are given by Janbu (1965) and Gibson *et al* (1981). The former gives a general formulation similar to Gibson *et al* (1967), and particular cases are considered. The latter uses the same general formulation as in an earlier paper (Gibson *et al*, 1967). Numerical solution for Gibson *et al* (1981) is provided by DeSimone and Viggiani (1976) using assumptions of constant coefficient of consolidation and logarithmic compressibility law.

Despite the fact that Gibson *et al*'s (1967, 1981) governing equation allows the general consideration of many factors influencing consolidation, other approximations are incorporated in order to arrive at a solution. This is a serious drawback to most extensive nonlinear theories, where mathematical difficulties usually arise for a general solution.

The advantages of ADINAT in such a situation is apparent since its finite element procedure, accompanied with the nonlinear solution strategies, provide a powerful

tool for solving any form of expression for material laws. Since different soils are subject to different forms of material laws, ADINAT allows the choice of the most proper constitutive relations based on experimental evidence rather than being restricted to any particular form due to analytical convenience.

4.2 Derivation of the General Governing Equation

The one dimensional consolidation of a simple clay layer with drainage at both top and bottom is used for the illustration here. (Gibson *et al*, 1967) The soil profile and coordinate systems employed are given in Fig. 4.1. Fig. 4.1(a) and (b) show the Lagrangian system and refers all events to the initial (zero time) state. The convective coordinate, on the other hand, always moves with the actual material configuration. This is described in Fig. 4.1(c) and (d).

To further clarify the following derivation, a pictorial description of the stress distribution in the soil layer in the convective coordinate system is shown in Fig. 4.2. In the following derivation, the first seven assumptions stated in Section 3.1 are still valid.

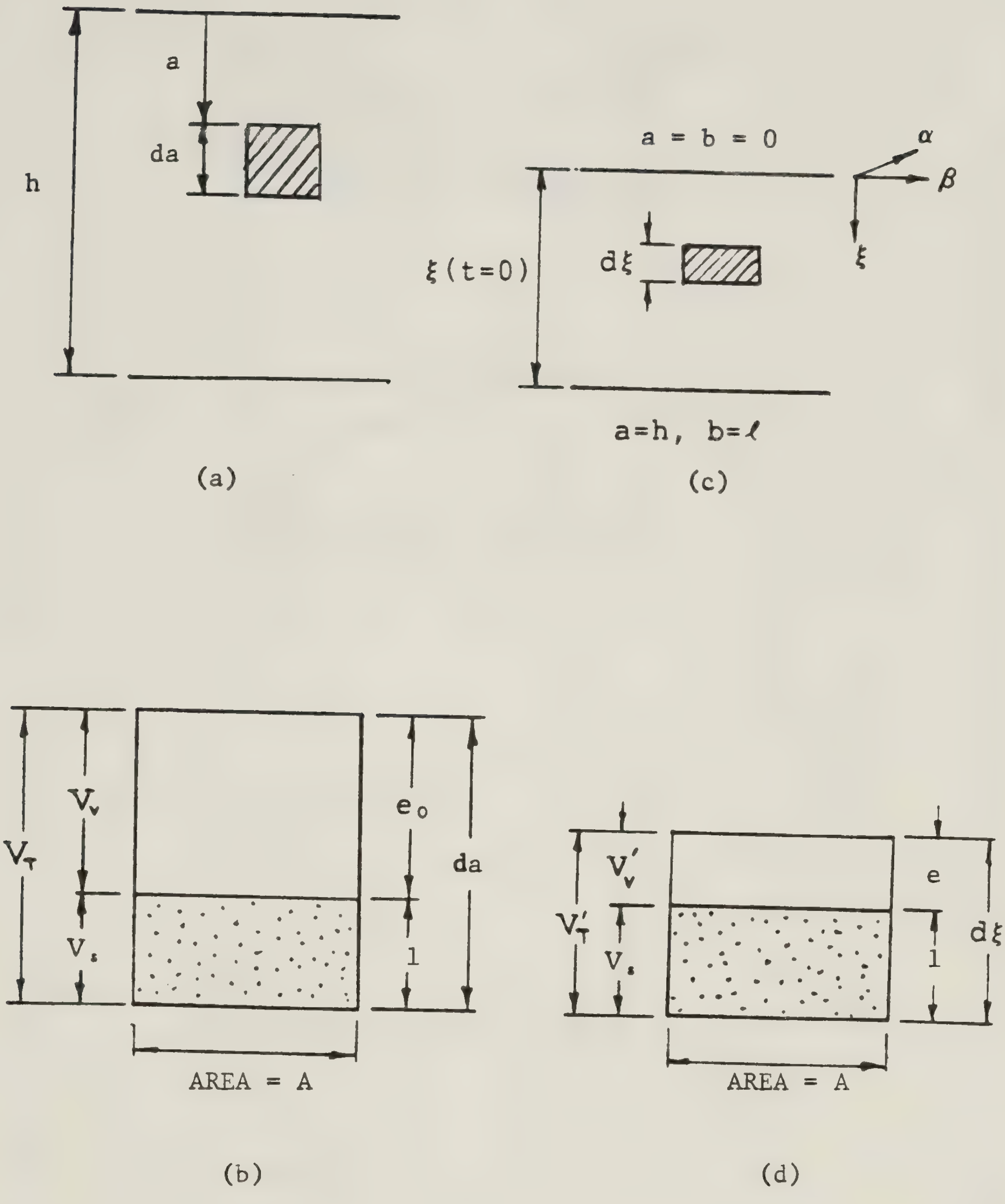


Figure 4.1 Coordinate system: (a),(b) Lagrangian: initial state, (c),(d) Convective: consolidating state

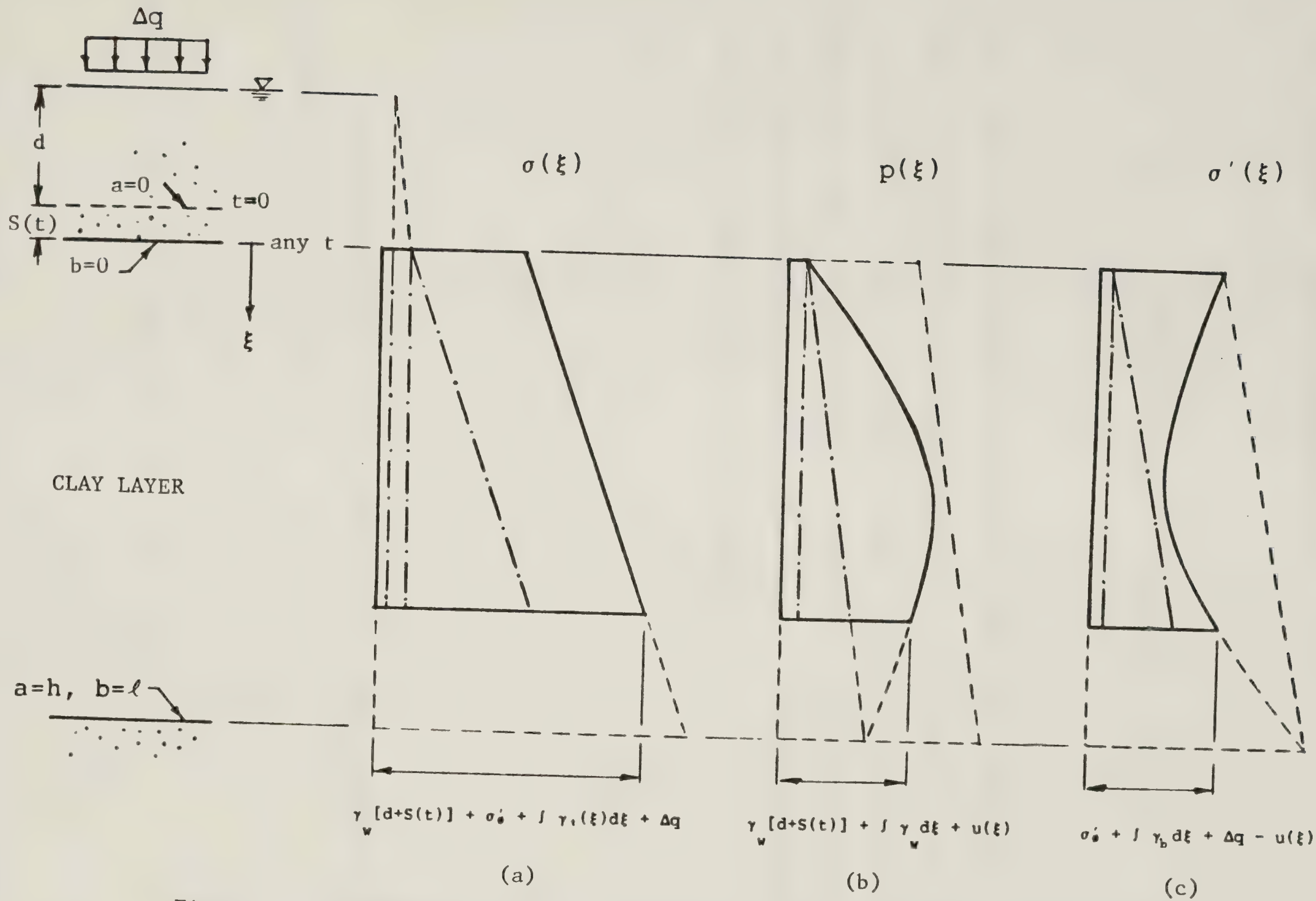


Figure 4.2 Stress and pore pressure distribution in convective coordinate

Referring to the convective system ξ in Fig. 4.2, the total stress σ can be expressed as

$$\sigma(\xi) = \gamma_w [d+S(t)] + \sigma_0' + \int \gamma_t(\xi)d\xi + \Delta q \qquad (4.1)$$

d is the distance between the water table and the soil layer, S(t) is the settlement at time t, γ_t and γ_w are the unit weight of soil and water respectively. Differentiating partially with respect to ξ, $\xi = \xi(a,t)$, and tranforming into the Lagrangian system by the chain rule, a vertical equilibrium equation can be obtained

$$\frac{\partial\sigma}{\partial a} - \frac{\gamma_s+e\gamma w}{1+e}\cdot\frac{\partial\xi}{\partial a} = 0 \qquad (4.2)$$

The expression for pore pressure in the convective system from Fig. 4.2 is

$$p(\xi) = \gamma_w [d+S(t)] + \int \gamma_w d\xi + u(\xi) \qquad (4.3)$$

Similarly as above, equilibrium of the pore fluid can be

determined,

$$\frac{\partial u}{\partial a}\cdot\frac{\partial a}{\partial \xi} = \frac{\partial p}{\partial a}\cdot\frac{\partial a}{\partial \xi} - \gamma_w \tag{4.4}$$

The net inflow rate of fluid weight is

$$q_\xi - (q_\xi + dq_\xi) = -\frac{\partial}{\partial \xi}\left[(v_w - v_s)\frac{e\gamma w}{1+e}\right]\cdot d\xi d\alpha d\beta \tag{4.5}$$

and the rate of change of fluid weight can be given as

$$\frac{\partial}{\partial t}(W_w) = \frac{\partial}{\partial t}\left[\frac{e\gamma w}{1+e}\cdot d\xi d\alpha d\beta\right] \tag{4.6}$$

By continuity, equating the above two equations and putting

$$\frac{\partial \xi}{\partial a} = \frac{1+e(a,t)}{1+e(a,0)} \tag{4.7}$$

gives

$$\frac{\partial}{\partial a}\left[(v_w - v_s)\frac{e\gamma_w}{1+e}\right] = - \frac{\partial}{\partial t}\left[\frac{e\gamma_w}{1+e}\cdot\frac{\partial \xi}{\partial a}\right] \tag{4.8}$$

By Darcy's law, the fluid flux is proportional to the excess pressure gradient as

$$(v_w - v_s)\,\frac{e\gamma_w}{1+e} = -k\,\frac{\partial u}{\partial a}\,\frac{\partial a}{\partial \xi} \tag{4.9}$$

Substituting Eq. 4.4 and Eq. 4.8 into the above equation, one obtains

$$\frac{\partial}{\partial a}\left[k\left(\gamma_w - \frac{\partial p}{\partial a}\cdot\frac{\partial a}{\partial \xi}\right)\right] = - \frac{\partial}{\partial t}\left[\frac{e\gamma_w}{1+e}\cdot\frac{\partial \xi}{\partial a}\right] \tag{4.10}$$

From Eq. 4.2, 4.7, 4.10 and the effective stress principle,

$$\sigma = \sigma' + p \tag{4.11}$$

gives

$$\frac{\partial}{\partial a}\left\{\frac{k}{1+e}\left[(1+e_0)\frac{\partial \sigma'}{\partial a} - (\gamma_s - \gamma_w)\right]\right\} = -\frac{\gamma_w}{1+e_0}\cdot\frac{\partial e}{\partial t} \tag{4.12}$$

Note that e_0 is not a constant but varies throughout the soil depth. Eq. 4.12 is a general governing equation with effective stress and void ratio as the primary unknowns.

4.3 Overview of ADINAT Application

4.3.1 General

One dimensional nonlinear theories can be classified into four main categories: small strain - thin layer, small strain - thick layer, finite strain - thin layer and finite strain - thick layer analyses. Applications of ADINAT to each category will be illustrated.

Mathematically, small strain requires the volume at any time t, (1+e), is equal to the initial volume $(1+e_0)$. Thin

layer analysis does not allow for the total stress variation with depth due to the self-weight of the soil mass, which means $\gamma_s = \gamma_w$. This first and second limitation individually is not imposed on the finite strain and thick layer analysis respectively.

General formulations used in ADINAT for each of these categories are derived below. Their uses will be discussed latter. Examples are provided in the following chapters.

4.3.2 Formulations of *ADINAT Equations*

(a) Small Strain and Thin Layer Analysis

As discussed previously, $(1+e)$ equals $(1+e_0)$ and γ_s equals γ_w are presumed for small strain and thin layer analysis. Further, the Lagrangian coordinate *a* can be replaced by the Eulerian coordinate *z*, since the initial configuration holds for all time. Using these simplifications in Eq 4.12,

$$\frac{\partial}{\partial z}\left[k \frac{\partial \sigma'}{\partial z} \right] = - \frac{\gamma w}{1+e_0} \frac{\partial e}{\partial t} \tag{4.13}$$

and further assuming

$$\sigma' = \sigma(e) \tag{4.14}$$

gives

$$\frac{\partial}{\partial z}\left[k \frac{\partial \sigma'}{\partial z} \right] = - \frac{\gamma w}{1+e_0} \frac{de}{d\sigma'} \frac{\partial \sigma'}{\partial t} \tag{4.15}$$

or in a different form

$$\frac{\partial}{\partial z}\left[- \frac{k}{\gamma_w} \frac{d\sigma'}{de} \frac{\partial e}{\partial z} \right] = \frac{1}{1+e_0} \frac{\partial e}{\partial t} \tag{4.16}$$

which can be rewritten as

$$\frac{\partial}{\partial z}\left\{ \frac{k}{\gamma_w}\left[-(1+e_0)\frac{d\sigma'}{de}\right] \frac{\partial e}{\partial z} \right\} = \frac{\partial e}{\partial t} \tag{4.17}$$

Since

$$u(z,t) = \sigma'_0 + \Delta q - \sigma'(z,t) \tag{4.18}$$

Differentiating partially with respect to *z* and *t* gives

$$\frac{\partial u}{\partial z} = - \frac{\partial \sigma'}{\partial z} \tag{4.19}$$

and

$$\frac{\partial u}{\partial t} = - \frac{\partial \sigma'}{\partial t} \tag{4.20}$$

Substituting these equations in Eq. 4.15 and Eq. 4.17, together with the conventional definitions of Cv, Eq. 3.7, and m_v, Eq. 3.8, result in

$$\frac{\partial}{\partial z} \left[k \frac{\partial u}{\partial z} \right] = \gamma_w m_v \frac{\partial u}{\partial t} \tag{4.21}$$

and

$$\frac{\partial}{\partial z}\left[Cv \frac{\partial e}{\partial z} \right] = \frac{\partial e}{\partial t} \tag{4.22}$$

(b) Small Strain and Thick Layer Analysis

Assume small strain, $(1+e) \simeq (1+e_0)$ and thus replace a by the Eulerian coordinate z in Eq. 4.12, which can be rewritten as

$$\frac{\partial}{\partial z}\{k\frac{\partial \sigma'}{\partial z} - \frac{k}{1+e_0}(\gamma_s - \gamma_w)\} = -\frac{\gamma w}{1+e_0}\frac{\partial e}{\partial t} \tag{4.23}$$

In thick layer analysis using the Eulerian coordinate, self-weight of soil mass is to be accounted for in the effective stress relationship as

$$\sigma'(z,t) = \sigma'_{\emptyset} + \Delta q + \int(\gamma_t - \gamma_w)dz - u(z,t) \tag{4.24}$$

or

$$\sigma'(z,t) = \sigma'_{\phi} + \Delta q + (\gamma_s - \gamma_w)\cdot\int \frac{dz}{1+e_o} - u(z,t) \qquad (4.25)$$

The subscript ϕ refers to the initial value at soil surface. Differentiating partially with respect to z and t give

$$\frac{\partial\sigma'}{\partial z} = \frac{\gamma_s - \gamma w}{1+e_o} - \frac{\partial u}{\partial t} \qquad (4.26)$$

and

$$\frac{\partial\sigma'}{\partial t} = -\frac{\partial u}{\partial t} \qquad (4.27)$$

Substituting Eq. 4.14, 4.26 and 4.27 into Eq. 4.23, gives

$$\frac{\partial}{\partial z}\left[k\frac{\partial u}{\partial z}\right] = \gamma_w m_v \frac{\partial u}{\partial t} \qquad (4.28)$$

(c) Finite Strain and Thin Layer Analysis

For finite strain and thin layer formulation, setting $\gamma_s \simeq \gamma_w$ in Eq. 4.12 obtains

$$\frac{\partial}{\partial a}\left[k\frac{1+e_0}{1+e} \frac{\partial \sigma'}{\partial a} \right] = - \frac{\gamma w}{1+e_0} \frac{\partial e}{\partial t} \tag{4.29}$$

Assuming Eq. 4.14 and using the definitions of Eq. 3.7 and Eq. 3.8, Eq. 4.29 can be expressed as

$$\frac{\partial}{\partial a}\left[k\frac{1+e_0}{1+e} \frac{\partial \sigma'}{\partial a} \right] = \gamma_w \frac{mv(1+e)}{1+e_0} \frac{\partial \sigma'}{\partial t} \tag{4.30}$$

or

$$\frac{\partial}{\partial a}\left[\frac{Cv(1+e_0)}{(1+e)^2} \frac{\partial e}{\partial a}\right] = \frac{1}{1+e_0} \frac{\partial e}{\partial t} \tag{4.31}$$

Since

$$u(a,t) = \sigma_0' + \Delta q - \sigma'(a,t) \tag{4.32}$$

in thin layer analysis. σ_0' refers to the initial effective stress in soil. Differentiating partially with respect to *a* and *t* similar to Section (a), and substituting into Eq. 4.30, gives:

$$\frac{\partial}{\partial a}\left[k \frac{1+e_0}{1+e} \frac{\partial u}{\partial a} \right] = \gamma_w \frac{m_v(1+e)}{1+e_0} \frac{\partial u}{\partial t} \tag{4.33}$$

(d) Finite Strain and Thick Layer Analysis

To account for both large deformation and self-weight in finite strain and thick layer formulation, the convective system should be considered. The effective stress relation is

$$\sigma'(\xi) = \sigma_\emptyset' + \Delta q + \int(\gamma_t - \gamma_w)d\xi - u(\xi) \tag{4.34}$$

or it can be determined in Lagrangian coordinate through

$$\sigma'(a,t) = \sigma_0' + \Delta q + (\gamma_s - \gamma_w) \cdot \int \frac{da}{1+e_o} - u(a,t) \qquad (4.35)$$

which gives

$$\frac{\partial \sigma'}{\partial a} = \frac{\gamma_s - \gamma w}{1+e_o} - \frac{\partial u}{\partial a} \qquad (4.36)$$

and

$$\frac{\partial \sigma'}{\partial t} = - \frac{\partial u}{\partial t} \qquad (4.37)$$

Substituting Eq. 4.36 into Eq. 4.12 gives:

$$\frac{\partial}{\partial a}\left[- \frac{k(1+e_o)}{1+e} \frac{\partial u}{\partial a} \right] = - \frac{\gamma w}{1+e_o} \frac{\partial e}{\partial t} \qquad (4.38)$$

Substituting Eq. 4.14 and 4.37 into Eq. 4.38 and rearranging to obtain

$$\frac{\partial}{\partial a}\left[k \frac{1+e_o}{1+e} \frac{\partial u}{\partial a} \right] = \gamma_w \frac{mv(1+e)}{1+e_o} \frac{\partial u}{\partial t} \tag{4.39}$$

Since $(1+e_o)$ varies with depth, another reduced coordinate *b* may be used. This coordinate may be physically interpreted as the volume of soil solids lying between the datumn and the point being considered, that is (McNabb, 1960)

$$b(a) = \int \frac{da}{1+e(a,0)} \tag{4.40}$$

or

$$\frac{db}{da} = \frac{1}{1+e_o} \tag{4.41}$$

The mathematics of the effective stress relation now becomes a little simplier,

$$\sigma'(b,t) = \sigma'_\emptyset + \Delta q + (\gamma_s - \gamma_w)b - u(b,t) \tag{4.42}$$

Substitute Eq. 4.41 into Eq. 4.39 produces,

$$\frac{\partial}{\partial b}\left[\frac{k}{1+e} \frac{\partial u}{\partial b} \right] = \gamma_w m_v (1+e)\frac{\partial u}{\partial t} \tag{4.43}$$

In reduced coordinates, the soil layer thickness is reduced to ℓ, which is obtained from the integral, Eq. 4.40, evaluated throughout the depth.

4.3.3 Remark on the Use of *ADINAT Equations*

A summary table of the above *ADINAT equations* is given in Fig. 4.3. The equations are renumbered from *A1* to *A9* in the figure for the convenience of later reference. Equations *A1* and *A2* are Eq. 4.21 and Eq. 4.22 respectively. *A3* is an obvious outcome from Eq. 4.21 when the parameter m_v is assumed constant. *A4* refers to Eq. 4.28 while *A5* is a direct result by assuming m_v constant. *A6*, *A7*, *A8*, *A9* are corresponding to Eq. 4.33, 4.31, 4.39, 4.43 respectively.

Notice that even if the forms of equation *A1* and *A4* are similar, their uses are different. For the application of ADINAT, *A4* must be evaluated as described in Chapter 6.

The purpose of Fig. 4.3 is to facilitate the users study of nonlinear consolidation using ADINAT. The

SMALL STRAIN

THIN LAYER

A1:
$$\frac{\partial}{\partial z}\left[k\frac{\partial u}{\partial z}\right] = \gamma_w m_v \frac{\partial u}{\partial t}$$

A2:
$$\frac{\partial}{\partial z}\left[C_v\frac{\partial e}{\partial z}\right] = \frac{\partial e}{\partial t}$$

A3:
$$\frac{\partial}{\partial z}\left[C_v^m\frac{\partial u}{\partial z}\right] = \frac{\partial u}{\partial t}$$

$$u(z,t) = \sigma_o' + \Delta q - \sigma'(z,t)$$

THICK LAYER

A4:
$$\frac{\partial}{\partial z}\left[k\frac{\partial u}{\partial z}\right] = \gamma_w m_v \frac{\partial u}{\partial t}$$

A5:
$$\frac{\partial}{\partial z}\left[C_v^m\frac{\partial u}{\partial z}\right] = \frac{\partial u}{\partial t}$$

$$u(z,t) = \sigma_o' + \Delta q + \int(\gamma_s-\gamma_w)dz - \sigma'(z,t)$$

$$u(z,t) = \sigma_o' + \Delta q + (\gamma_s-\gamma_w)\cdot\int\frac{dz}{1+e_o} - \sigma'(z,t)$$

FINITE STRAIN

THIN LAYER

A6:
$$\frac{\partial}{\partial a}\left[\frac{k(1+e_o)}{1+e}\frac{\partial u}{\partial a}\right] = \gamma_w\frac{m_v(1+e)}{1+e_o}\frac{\partial u}{\partial t}$$

A7:
$$\frac{\partial}{\partial a}\left[C_v\left(\frac{1+e_o}{1+e}\right)^2\frac{\partial e}{\partial a}\right] = \frac{\partial e}{\partial t}$$

$$u(a,t) = \sigma_o' + \Delta q - \sigma'(a,t)$$

THICK LAYER

A8:
$$\frac{\partial}{\partial a}\left[\frac{k(1+e_o)}{1+e}\frac{\partial u}{\partial a}\right] = \gamma_w\frac{m_v(1+e)}{1+e_o}\frac{\partial u}{\partial t}$$

A9:
$$\frac{\partial}{\partial b}\left[\frac{k}{1+e}\frac{\partial u}{\partial b}\right] = \gamma_w m_v(1+e)\frac{\partial u}{\partial t}$$

$$u(a,t) = \sigma_o' + \Delta q + (\gamma_s-\gamma_w)\cdot\int\frac{da}{1+e_o} - \sigma'(a,t)$$

$$u(b,t) = \sigma_o' + \Delta q + (\gamma_s-\gamma_w)b - \sigma'(b,t)$$

NOTES

1. Major assumptions: no secondary effect; stress history is neglected.
2. z:Eulerian, a:Lagrangian, b:reduced coordinate; db/da=1/1+e(a,0).
3. k, m_v can be constants or variables.
4. $m_v = -\frac{1}{1+e}\cdot\frac{de}{d\sigma'}$, whereas $1+e = 1+e_o$ in small strain analysis.
5. $C_v = k/(\gamma_w \cdot m_v)$, it can be a constant with variable(s) k and/or m_v.
6. C_v^m: C_v with constant m_v.

Figure 4.3 General formulations for ADINAT applications in nonlinear consolidation

equations given in each category, although in different forms, are equivalent. This will further assist the use of the table. The table can be used in many ways. Examples will be shown in the succeeding chapters.

In these equations, Cv and m_v are just notations presented in the conventional way. They are different from the mean values $\overline{Cv}$, $\overline{m_v}$ obtained from the conventional tests, and can be substituted by any appropriate expressions according to their basic definitions, Eq. 3.7 and 3.8. Unless otherwise stated, the material parameters can be constants or variables.

Since the logarithmic material relations are so widely accepted that a table of the finite strain - thin layer analysis with this approximation is given in Fig. 4.4. Several letter symbols adopted in the figure are defined below. α is the commonly used load ratio,

$$\alpha = \sigma'_f / \sigma'_0 \qquad (4.44)$$

and β is the permeability ratio,

MEAN VALUES FROM TESTS

B1:

$$\frac{\partial}{\partial a}\left\{\frac{C_1\bar{k}}{\bar{m}_v}\frac{1}{1+e}\frac{\partial u}{\partial a}\right\} = (1+e)\frac{\partial u}{\partial t}$$

$[e-\sigma', e_o, \bar{k}, \bar{m}_v]^*$

B2:

$$\frac{\partial}{\partial a}\left\{C_2\frac{\bar{C}_v}{(1+e)^2}\frac{\partial e}{\partial a}\right\} = \frac{\partial e}{\partial t}$$

$[e-\sigma', e_o, \bar{C}_v]$

B3:

$$\frac{\partial}{\partial a}\left\{\frac{\bar{C}_v}{(1-\mu\varepsilon_f)^2}\frac{\partial \mu}{\partial a}\right\} = \frac{\partial \mu}{\partial t}^{+}$$

$[\varepsilon_f (\text{or } e_o \,\&\, e_f), \bar{C}_v]$

$C_1 = C_2/\gamma_w$

$C_2 = (1+e_o)^2$

$e - \log_{10}\sigma'$

B4:

$$\frac{\partial}{\partial a}\left\{\frac{C_3 k}{1+e_o - C_c\log_{10}[(\sigma_f'-u)/\sigma_o']}\frac{\partial u}{\partial a}\right\} = \frac{1}{\sigma_f'-u}\frac{\partial u}{\partial t}$$

$[\sigma_o', \sigma_f' (\text{or } e_f), e_o, C_c, k]$

B5:

$$\frac{\partial}{\partial a}\left\{C_4\frac{k\,10^{(e_o-e)/C_c}}{1+e}\frac{\partial e}{\partial a}\right\} = \frac{\partial e}{\partial t}$$

$[\sigma_o', e_o, e_f (\text{or } \sigma_f'), C_c, k]$

B6:

$$\frac{\partial}{\partial a}\left\{C_5\frac{k\alpha^{\mu}}{1-\mu\varepsilon_f}\frac{\partial \mu}{\partial a}\right\} = \frac{\partial \mu}{\partial t}$$

$[\sigma_o', \sigma_f', \varepsilon_f (\text{or } e_o \,\&\, e_f), k]$

$C_3 = \ln 10(1+e_o)^2/(\gamma_w C_c)$

$C_4 = \sigma_o' C_3$

$C_5 = C_{vf}/k_o$

$e - \log_{10}\sigma'$
$e - \log_{10}k$

B7:

$$\frac{\partial}{\partial a}\left\{\frac{C_6[(\sigma_f'-u)/\sigma_o']^{-\nu}}{1+e_o - C_c\log_{10}[(\sigma_f'-u)/\sigma_o']}\frac{\partial u}{\partial a}\right\} = \frac{1}{\sigma_f'-u}\frac{\partial u}{\partial t}$$

$[\sigma_o', \sigma_f' (\text{or } e_f), e_o, C_c, C_k, k_o]$

B8:

$$\frac{\partial}{\partial a}\left\{C_7\frac{10^{\nu_r(e_o-e)}}{1+e}\frac{\partial e}{\partial a}\right\} = \frac{\partial e}{\partial t}$$

$[\sigma_o', e_o, e_f (\text{or } \sigma_f'), C_c, C_k, k_o]$

B9:

$$\frac{\partial}{\partial a}\left\{C_{vf}\frac{\alpha^{(1-\nu)\mu}}{1-\mu\varepsilon_f}\frac{\partial \mu}{\partial a}\right\} = \frac{\partial \mu}{\partial t}$$

$[\sigma_o', \sigma_f', \varepsilon_f (\text{or } e_o \,\&\, e_f), C_c/C_k, k_o]$

OR: $[\sigma_o', e_o, e_f (\text{or } \sigma_f'), C_c, C_k, k_o]$

B10:

$$\frac{\partial}{\partial a}\left\{C_{vi}\frac{(\alpha\beta)^{\mu}}{1-\mu\varepsilon_f}\frac{\partial \mu}{\partial a}\right\} = \frac{\partial \mu}{\partial t}$$

$[\sigma_o', \sigma_f', \varepsilon_f (\text{or } e_o \,\&\, e_f), k_o, k_f]$

$C_6 = k_o C_3$

$C_7 = k_o \sigma_o' C_3$

$e - \sigma'^{p}$
$k/(1+e) - \sigma'^{q}$

B11:

$$\frac{\partial}{\partial a}\left\{C_8\sigma'^{q-p}\frac{\partial e}{\partial a}\right\} = \frac{\partial e}{\partial t}$$

$[e-\sigma', \sigma_o', \sigma_f', (\text{or } e_o, e_f), C_{vo}, q]$

B12:

$$\frac{\partial}{\partial a}\left\{C_8\sigma'^{q}\frac{\partial \sigma'}{\partial a}\right\} = \sigma'^{p}\frac{\partial \sigma'}{\partial t}$$

$[\sigma_o', \sigma_f', C_{vo}, p, q]$

$C_8 = \sigma_o'^{\,p-q} C_{vo}$

MATERIAL CONSTANTS:

$\alpha = \sigma_f'/\sigma_o'$

$\beta = k_f/k_o$

$\nu = C_c/C_k$

$\nu_r = \frac{1}{C_c} - \frac{1}{C_k}$

$\xi_f = \frac{e_o - e_f}{1+e_o}$

$C_{vo} = \frac{k_o(1+e_o)}{\gamma_w(de/d\sigma')_o}$

$C_{vf} = \frac{k_o\sigma_o'\ln\alpha}{\gamma_w\xi_f}$

Notes: * Basic parameters required for analysis

$^{+}\mu = \frac{e_o - e}{e_o - e_f}$; and $\frac{u}{u_o} = \frac{\alpha - \alpha^{\mu}}{\alpha - 1}$

Figure 4.4 Useful equations for ADINAT applications in finite strain, thin layer consolidation

$$\beta = k_f / k_0 \tag{4.45}$$

This ratio is always less than 1 in monotonic compression as in the illustrated examples. The constant ν is a ratio of the material coefficients

$$\nu = Cc / Ck \tag{4.46}$$

where Cc is the slope of the e-$\log_{10}\sigma'$ line, and Ck is the slope of the e-$\log_{10}k$ line. ν_r is defined in a similar way:

$$\nu_r = \frac{1}{Cc} - \frac{1}{Ck} \tag{4.47}$$

μ is termed local consolidation ratio and with a value ranges from 0 to 1. It is given by

$$\mu = \frac{e_0 - e}{e_0 - e_f} \tag{4.48}$$

The application of this variable simplifies the equations as

well as their use, as may be seen from Fig. 4.4. If the logarithmic effective stress - void ratio relation is assumed, the excess pore pressure ratio can be determined from μ as follows

$$\frac{u}{u_o} = \frac{\alpha - \alpha^{\mu}}{\alpha - 1} \tag{4.49}$$

The total final strain, ξ_f, is expressed in the form of

$$\xi_f = \frac{e_o - ef}{1 + e_o} \tag{4.50}$$

Cvi is the initial consolidation ratio defined as

$$Cvi = k_o\sigma_o'(1+e_o)\ln 10 \;/\; \gamma_w Cc$$

$$= k_o\sigma_o'\ln\alpha \;/\; \gamma_w \xi_f \tag{4.51}$$

Another approximation utilizing a more general material law used by Janbu (1963) and Koppula (1970) is

$$\frac{de}{d\sigma'} = \left[\frac{de}{d\sigma'} \right]_1 \left(\frac{\sigma'}{\sigma'_o}\right)^p \tag{4.52}$$

and

$$\frac{k}{1+e} = \left[\frac{k}{1+e} \right]_1 \left(\frac{\sigma'}{\sigma'_o}\right)^q \tag{4.53}$$

These are also given in Fig. 4.4. The constants p and q range between -1 and 0, the subscript 1 denotes a reference state. The logarithmic constitutive relations just mentioned are special cases of these equations.

Since average values of material parameters are often obtained from conventional laboratory tests, the formulations using these parameters are also included in Fig. 4.4. The values of $\overline{k}$, $\overline{m_v}$ and $\overline{Cv}$ are assumed to be obtained independently from tests. Note that $\overline{Cv}$ may not be equal to $\overline{k}/(\gamma_w \cdot \overline{m_v})$.

For the same reason as above, sets of different forms but mathematically equivalent equations are given in Fig. 4.4. Derivations of these equation are long but similar to those in Fig. 4.3 and will not be shown. Equations in the figure are numbered from *B1* to *B12* for

future reference.

All of these *ADINAT equations* in Fig. 4.3 and Fig. 4.4 are presented in a clear manner for ADINAT input, and are given in the following form:

$$\frac{\partial}{\partial x}\left[K\frac{\partial\theta}{\partial x}\right] = M\frac{\partial\theta}{\partial t} \tag{4.54}$$

where x, θ, K, M represents the coordinate, unknown, permeability, compressibiltiy variable respectively. To illustrate, whatever expression is entered in the *position* 'K' will be input as the permeability variable in the program. The same applies to the rest of the parameters.

Equations with an unknown variable σ' are primary for obtaining pore pressure results, while those with an unknown e are mainly for computing deformations. Both of these, obviously, can be used for either purpose with supplemental programs to reduce the original output.

4.4 Discussion

It can be seen from Fig. 4.3 that pore pressure can still be maintained as the primary unknown. Hence the strain or void ratio is no longer a privileged variable in nonlinear analysis, as is believed by some researchers. (Mikasa, 1965; Janbu, 1965; Gibson *et al*, 1967 & 1981)

The difficulty with the general governing equation, Eq. 4.39, is that the settlement cannot be assessed directly. On the other hand, Gibson *et al*'s (1981) equation may be useful for computing soil settlement, if a solution can be easily obtained.

Regarding the use of the general equation, Eq. 4.39, inconvenience may seem to arise in the computation of soil thickness ℓ, or the evaluation of the integral Eq. 4.40. It is believed that this cannot be avoided in any analyses dealing with both finite strain and self-weight effects. These two quantities, however, are readily and accurately computed by simple computer-based techniques.

The general governing equation *A8* or *A9* (Fig. 4.3) is more useful than Eq. 4.12 since solutions are readily obtained by ADINAT for the former, while no general solution is yet available for the latter. Therefore, *A8* or *A9* represents the working governing equation for a general

treatment of one dimensional consolidation. Note again that both of these equations are basically equivalent to Eq. 4.12.

As mentioned before, most theories can be recovered from the proposed ADINAT formulations. Examples are given below.

Terzaghi's classical theory is an obvious outcome of *ADINAT A1* when k and m_v are assumed constant. The governing equation found by Davis and Raymond (1965) is equivalent to *A2* with constant Cv. Barden and Berry (1965), Raymond (1966) are particular cases of *A1* where logarithmic material relations are used.

Analyses of soils with large depth by Schiffman and Gibson (1964), Raymond (1969), Davis (1971), Viggiani (1973) are special cases of ADINAT small strain - thick layer formulation, *A4*. In comparison with *A8*, Schiffman and Gibson's (1964) general equation is still deficient in the context of thick layer formulation.

McNabb (1960) has given an equation similar to *A7*. The equation given by Poskitt (1969) can be obtained from *A6* with the logarithmic material properties and change of variables. It is identical to equation *B10* in Fig. 4.4. Gibson *et al* (1967), Simons and Beng (1969), Wilson and

Hwang (1969) are particular cases of *A7*. Notice that the parameter Cv mentioned in the paper by Gibson *et al* is actually a mean value $\overline{Cv}$ in which $(1+e) \simeq (1+e_0)$ is implied.

The general governing equation Eq. 13 in Gibson *et al* (1967) or Eq. 19 in Gibson *et al* (1981) is basically identical to *A8* or *A9* respectively. Solutions are provided for *A8* and *A9* using ADINAT but no general solution has yet found for Gibson *et al*'s equation. Numerical solutions are given, however, only for an approximate form of the latter. (DeSimone and Viggiani, 1976; Gibson *et al*, 1981)

5. APPLICATION OF ADINAT IN NONLINEAR CONSOLIDATION OF THIN SAMPLE

5.1 General

In order to verify the proposed equations in Fig. 4.3 and show their applications, a series of examples, most of which are taken from published papers, are presented. Thin layer formulations, which most of these papers considered, are discussed in this chapter. Applications of thick layer theories will be given in the next chapter.

Another purpose of these examples is to show the correlation among the mathematical equivalent counterparts in the same category. Therefore, as many as possible will be used in the same example. Applications of the equations in Fig. 4.4 will also be illustrated as well.

ADINAT equations in Fig. 4.3 and Fig. 4.4 are referred to as *A1*, ... and *B1*, ... in the following examples. It is worthwile to note again that equations in Fig. 4.3 are *general* equations. That is, they can be used for any material laws. Equations in Fig. 4.4 are special cases of the finite strain - thin layer formulations in Fig. 4.3, with the assumed constitutive relations shown at the top of each sub-category.

In these two figures, equations in each set are mathematically equivalent and are presented in a simplified manner. The choice among them is a matter of preference or may depend on the primary output of the unknown variable.

For all examples illustrated here, unless otherwise specified, one dimensional linear finite element model is used, twenty equally spaced elements are assumed for the compressible layer. Ten solution time steps are assumed. Lumped compressibility matrix option and the Euler backward integration method are employed.

5.2 Examples of Samarasinghe-Huang-Drnevich Study

<u>*Objective*</u>*:*

To show ADINAT application in Samarasinghe *et al* (1982) studies.

<u>*ADINAT Nonlinear Equation*</u>*: A1, A6, B4, B5, B6*

<u>*Brief*</u>*:*

These authors have found that the permeability relation is determined by

$$k = C_k \frac{e^{n}}{1+e} \qquad (5.1)$$

where C_k is either a constant or it may vary with void ratio. They also assumed a common linear void ratio - logarithm effective stress relationship.

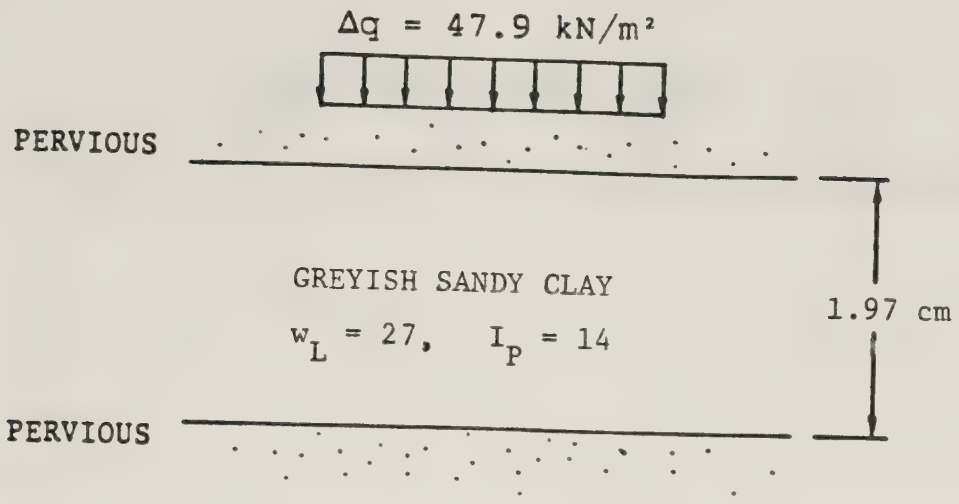
Description and Analysis:

An example of greyish sandy clay with the exponent $n=5.2$ and $C_k'=6.58\times10^{-4}$m/day obtained from Samarasinghe *et al* is illustrated here. Fig. 5.1 shows the soil profile, loading and boundary conditions. Material properties and the finite element model are also given in the figure.

Both small and finite strain analyses are performed for comparison. Since a logarithmic compressibility relationship is included, equations in Fig. 4.4 can be employed. Datafiles are given in Appendix A.11.

Results:

ADINAT prediction of pore pressure distribution at 50% consolidation is plotted in Fig. 5.2. Solutions with *A6* and *B4* are coincident since they are virtually the same equation. The small discrepancy among the results of *B4*, *B5* and *B6* may be due to the difference in numerical input into the program. The finite strain analysis in this example, is only little different from the small strain analysis.



PERMEABILITY MODEL:

$$k = C_k' \frac{e^n}{1 + e}$$

$C_k' = 6.58 \times 10^{-4}$ m/day

$n = 5.2$

COMPRESSIBILITY MODEL:

$e - \log \sigma'$

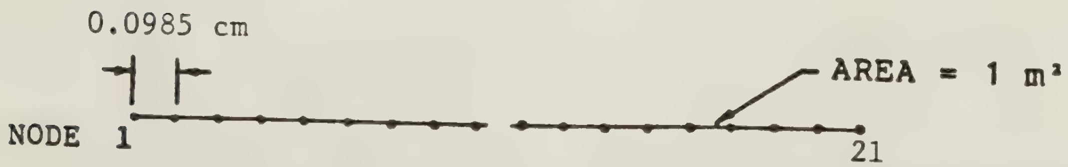
$C_c = 0.16$

OTHER PARAMETERS: $e_0 = 0.622$

$\sigma_0' = \Delta q$

$\gamma_w = 9.81$ kN/m³

FINITE ELEMENT MODEL FOR THE CLAY LAYER



20 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 5.1 One dimensional consolidation with nonlinear material properties: Samarasinghe et al, 1982

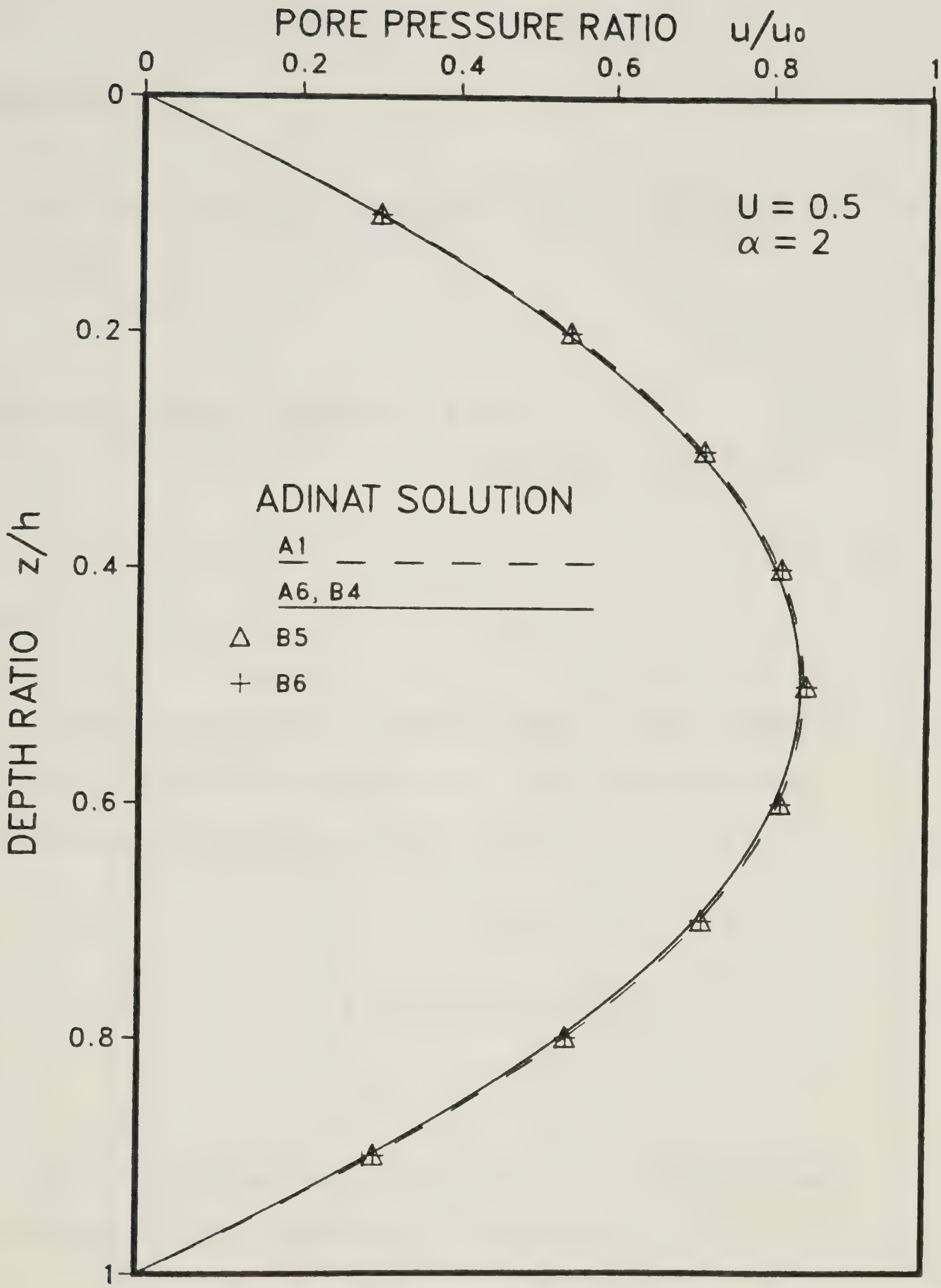


Figure 5.2 Pore pressure isochrones: thin layer analysis

5.3 Barden and Berry Analysis

Objective:

To show the use of ADINAT in a Barden and Berry (1965) analysis.

ADINAT Nonlinear Equation: (A) *A1*

(B) *A1, B1, B2, B3, B6*

Brief:

These authors have given a small strain theory utilizing logarithmic material laws. They further approximated the permeability relationship as

$$k = k_f (1+\eta' u^n) \qquad (5.2)$$

in which k_f is the value of k when $u=0$. η' and n are constants. Their equation is given as

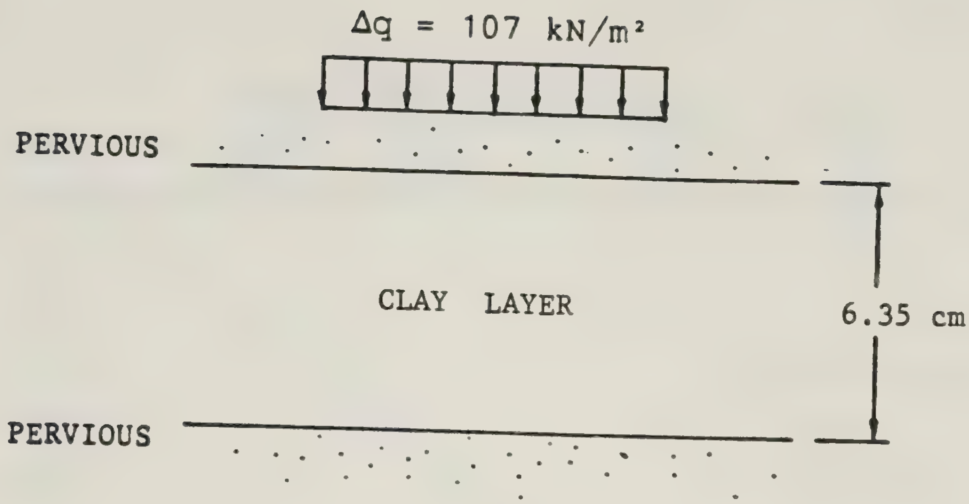
$$\frac{\partial}{\partial z}\left[\frac{kf}{\gamma_w}(1+bu^n)\frac{\partial u}{\partial z}\right] = \frac{.434Cc}{1+e_o}\,\frac{1}{\sigma_f - u}\,\frac{\partial u}{\partial t} \tag{5.3}$$

They resorted to finite difference method to solve the nonlinear equation generated.

Description and Analysis:

(A) An illustration of Barden and Berry's formulation with an assumed soil profile and material properties as given in Fig. 5.3 is presented. Values of 1 and 1/2, as referred to by Barden and Berry, are used for the value of n in Eq. 5.2.

(B) Results of a laboratory test given by Barden and Berry is analysed by ADINAT. Both small strain and finite strain analyses are illustrated. *B1*, *B2*, *B3* and *B6* in the finite strain formulations are included for comparison. The loading and material properties are shown in Fig. 5.5.



PERMEABILITY MODEL:

$k = k_f(1 + \eta' u^n)$

$\eta' = [(k_o/k_f)-1]/u_o^n$

$k_o = 4.18 \times 10^{-5}$ m/day

$k_f = 2.09 \times 10^{-5}$ m/day

$n = 1/2$ or 1

COMPRESSIBILITY MODEL:

$e - \log \sigma'$

$Cc = 0.4$

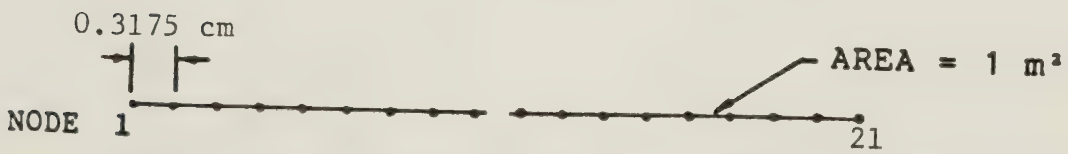
OTHER PARAMETERS:

$e_o = 0.959$

$\sigma_o' = \Delta q$

$\gamma_w = 9.81$ kN/m³

FINITE ELEMENT MODEL FOR THE CLAY LAYER



20 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 5.3 One dimensional consolidation with Barden-Berry (1965) formulation

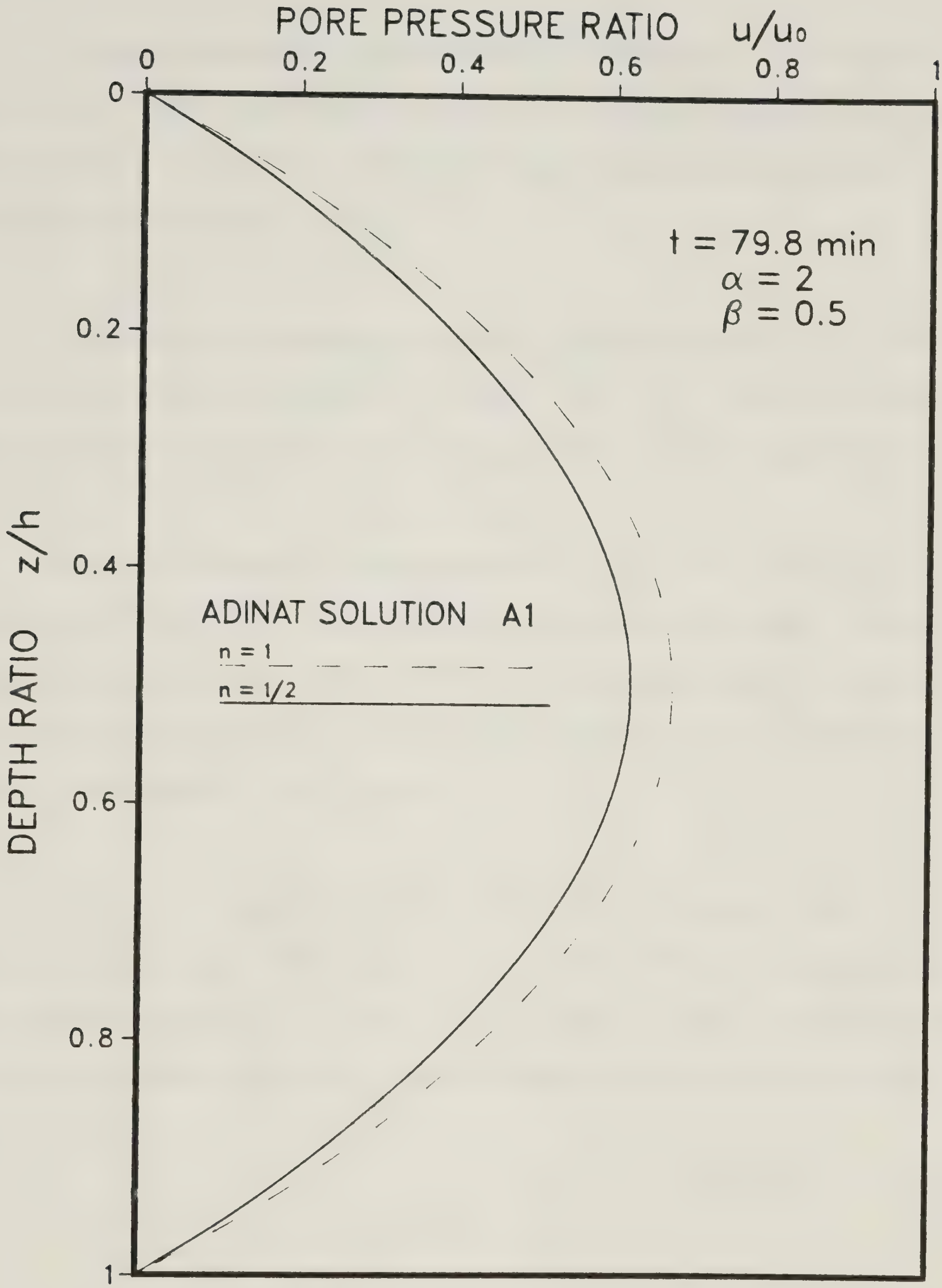


Figure 5.4 Pore pressure results in small strain - thin layer analysis

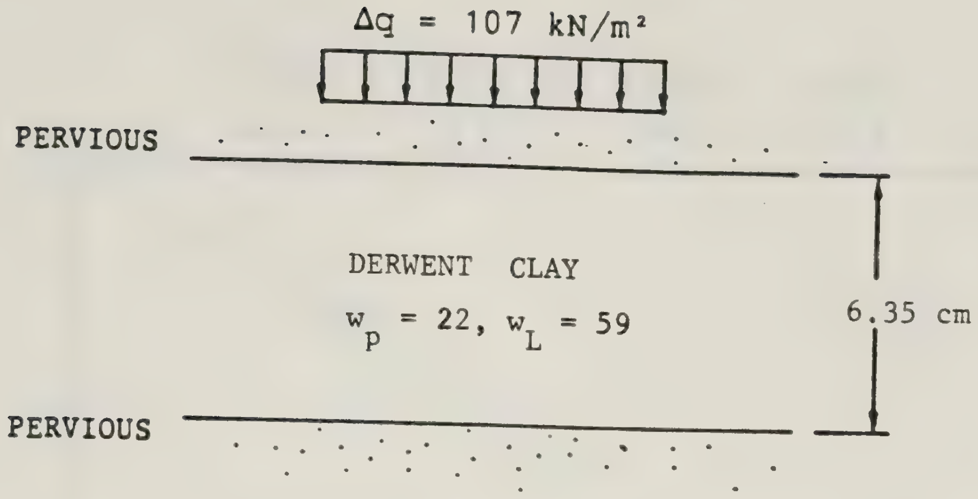
Results

(A)Pore pressures predicted by ADINAT are plotted in Fig. 5.4. Not much difference can be seen between the cases of n equals 1 and 1/2. This has also been observed by Barden and Berry as well.

(B)The pore pressure results given by ADINAT at 50% consolidation are plotted in Fig. 5.6. The finite strain solutions are found close to the small strain analysis.

The discrepancies among the finite strain results are due to the fact that different parameters are used. Note that the numerical value of $\overline{Cv}$ used in equations *B2* and *B3* is not exactly equal to $\overline{k}/(\gamma_w \cdot \overline{m}_v)$, whereas the parameters $\overline{k}$ and $\overline{m}_v$ are used in *B1* and *B6*.

Fig. 5.7 compares ADINAT predictions, Barden and Berry's solutions and the test results. The experimental settlement curve is fitted to the ADINAT curve to obtain the required time, which in turn is used to determine the pore pressures.



COMPRESSIBILITY MODEL:

$e - \log \sigma'$

$e_o = 0.959$

$Cc = 0.4$

$\sigma_o' = \Delta q$

MATERIAL PROPERTIES:

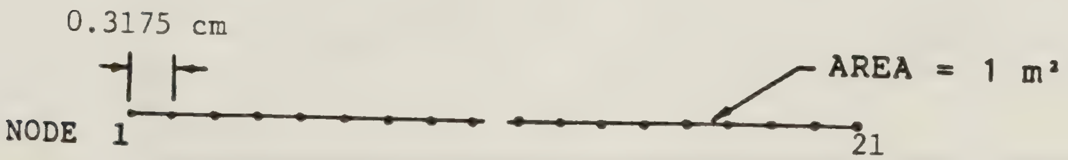
$\overline{k} = 2.09 \times 10^{-5}$ m/day

$\overline{m_v} = 6.34 \times 10^{-4}$ m²/kN

$\overline{Cv} = 3.39 \times 10^{-3}$ m²/day

$\gamma_w = 9.81$ kN/m³

FINITE ELEMENT MODEL FOR THE CLAY LAYER



20 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 5.5 Nonlinear consolidation analysis with experimental results

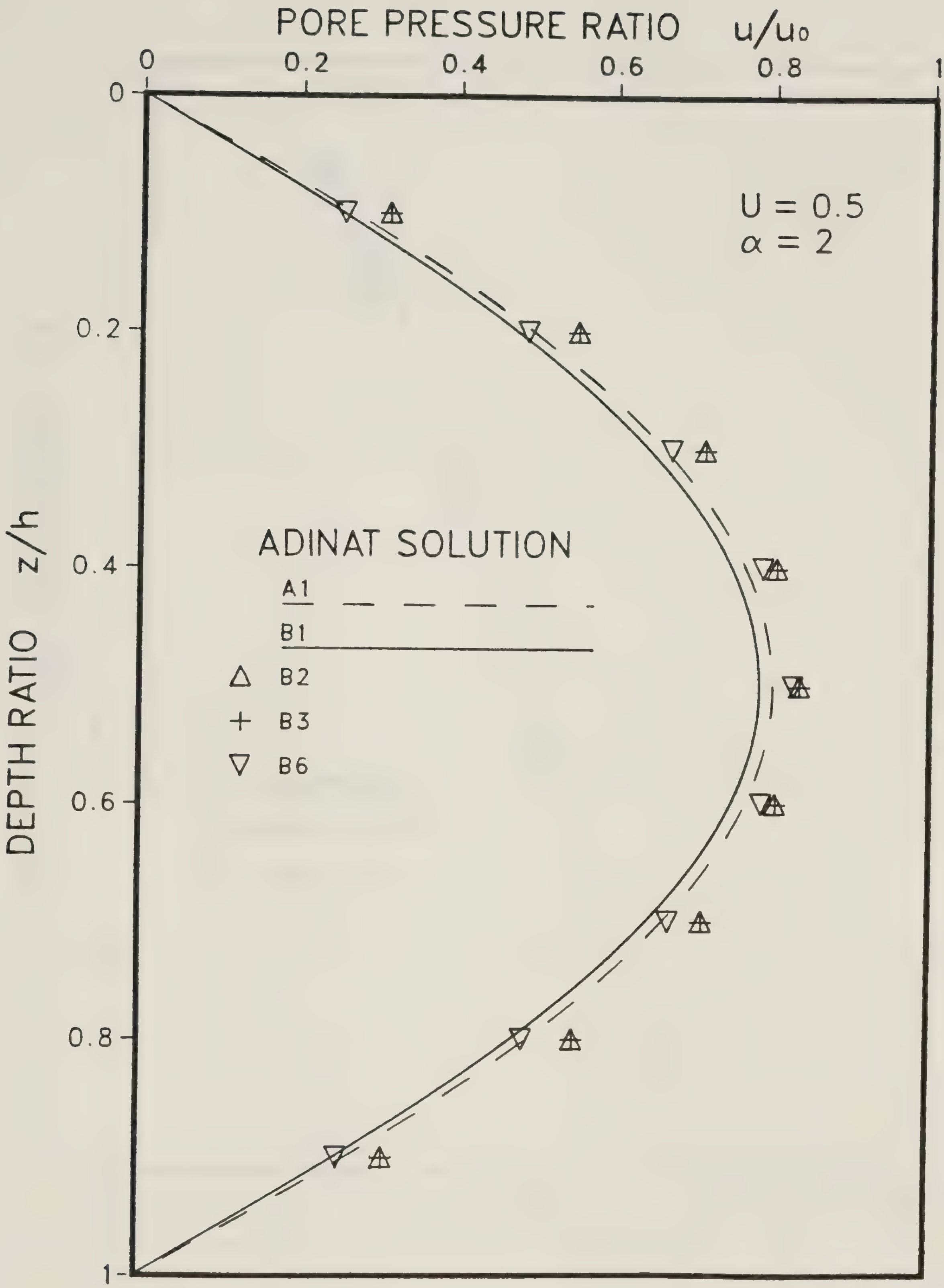


Figure 5.6 Pore pressure distribution in thin layer analysis

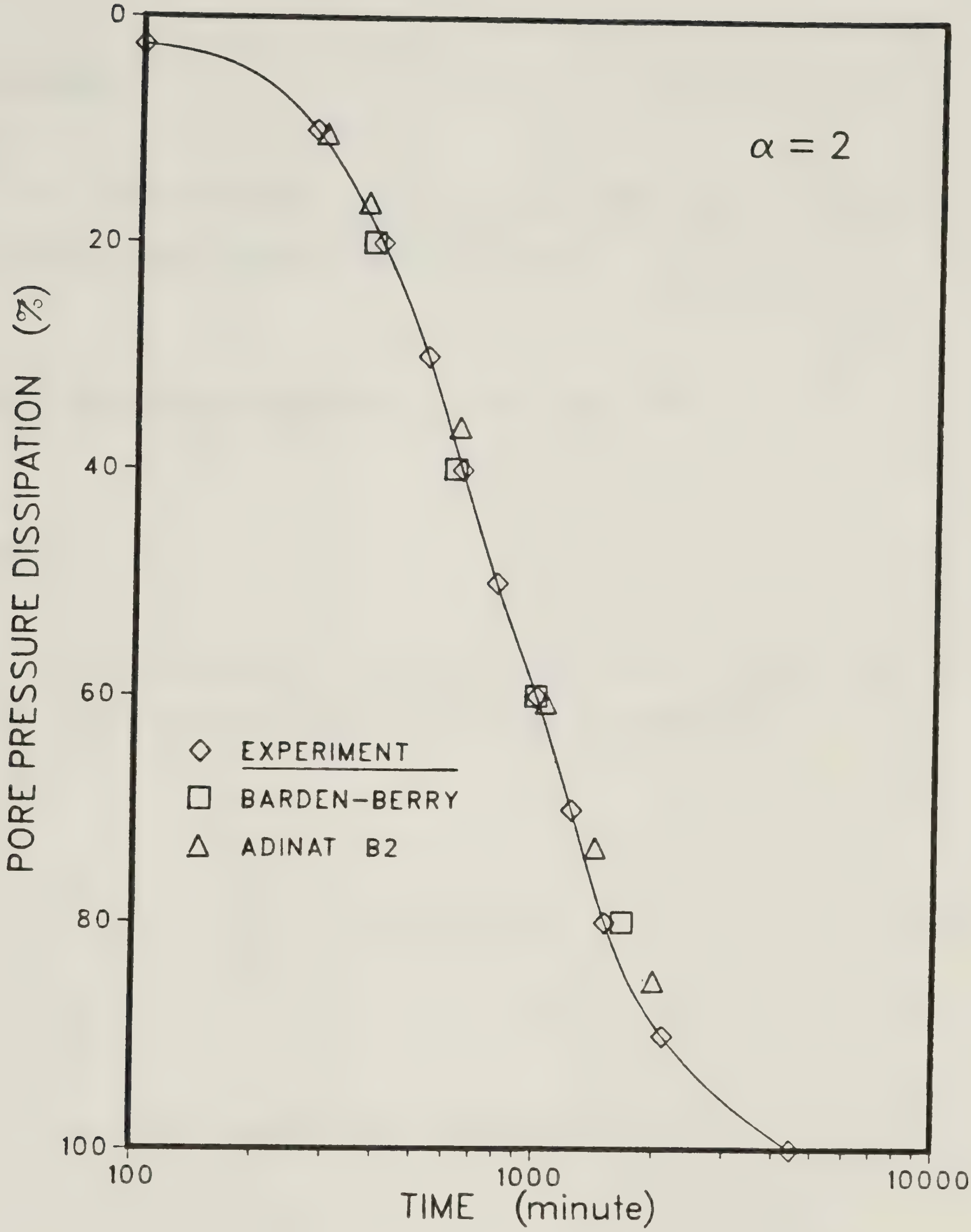


Figure 5.7 Pore pressure dissipation: small strain - thin layer analysis

5.4 Davis-Raymond Theory

Objective:

To verify ADINAT small strain - thin layer formulation with Davis and Raymond theory (1965).

ADINAT Nonlinear Equation: A1, A2, B2, B3

Brief:

These authors have given a small strain theory for thin layer and the governing equation is expressed as

$$-\overline{Cv}\left[\frac{1}{\sigma'}\frac{\partial^2 u}{\partial z^2}+\left(\frac{1}{\sigma'}\right)^2\left(\frac{\partial u}{\partial z}\right)^2\right]=\frac{1}{\sigma'}\frac{\partial \sigma'}{\partial t} \qquad (5.4)$$

It can be rearranged into a different form

$$\overline{Cv}\frac{\partial^2 \omega}{\partial z^2}=\frac{\partial \omega}{\partial t} \qquad (5.5)$$

with

$$\omega = \log_{10} \frac{\sigma'}{\sigma'_f} \tag{5.6}$$

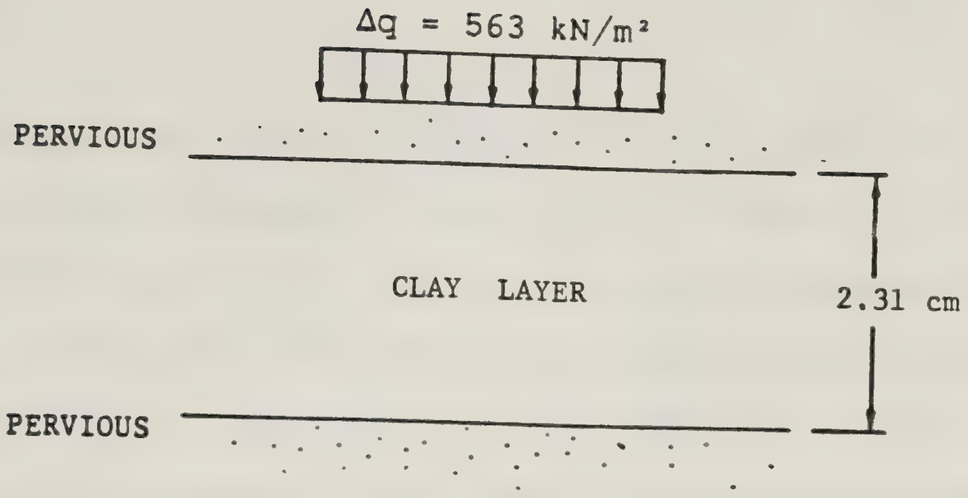
The general solution can be determined through

$$u = \sigma'_f [1-(\sigma'_0/\sigma'_f)^B] \tag{5.7}$$

B is Terzaghi's excess pore pressure ratio. Eq. 5.4 or 5.5 is a special case of equation *A2*, and Davis and Raymond have assumed the logarithmic compressibility law and that the coefficient of consolidation is constant.

Description and Analysis:

The soil profile, loading and material properties are given in Fig. 5.8. Finite strain analyses are also carried out with equations *B2* and *B3*. Eq. 21 in Davis and Raymond (Eq. 5.5 in above) is directly solved using ADINAT as well. Terzaghi's theory is also analysed by the program for comparisons. Datafiles are attached to Appendix A.13.



MATERIAL MODEL: $e - \log \sigma'$

CONSTANT Cv

MATERIAL PROPERTIES:

$e_o = 0.9$

$\sigma_o' = 188 \ kN/m^2$

$\gamma_w = 9.81 \ kN/m^3$

$Cc = 0.6$

$\overline{Cv} = 8.9 \times 10^{-4} \ m^2/day$

FINITE ELEMENT MODEL FOR THE CLAY LAYER

20 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 5.8 One dimensional nonlinear analysis with constant coefficient of consolidation

Results:

ADINAT pore pressure results at Tv=0.4 and with a load ratio of 4 are presented in Fig. 5.9. The small strain formulations agree well with the closed-form solutions using Eq. 5.7. Solutions with *A2* and with Davis and Raymond's Eq. 21 are almost identical, as they should be. The finite strain solution shows a lower prediction while Terzaghi's theory gives an even lower result.

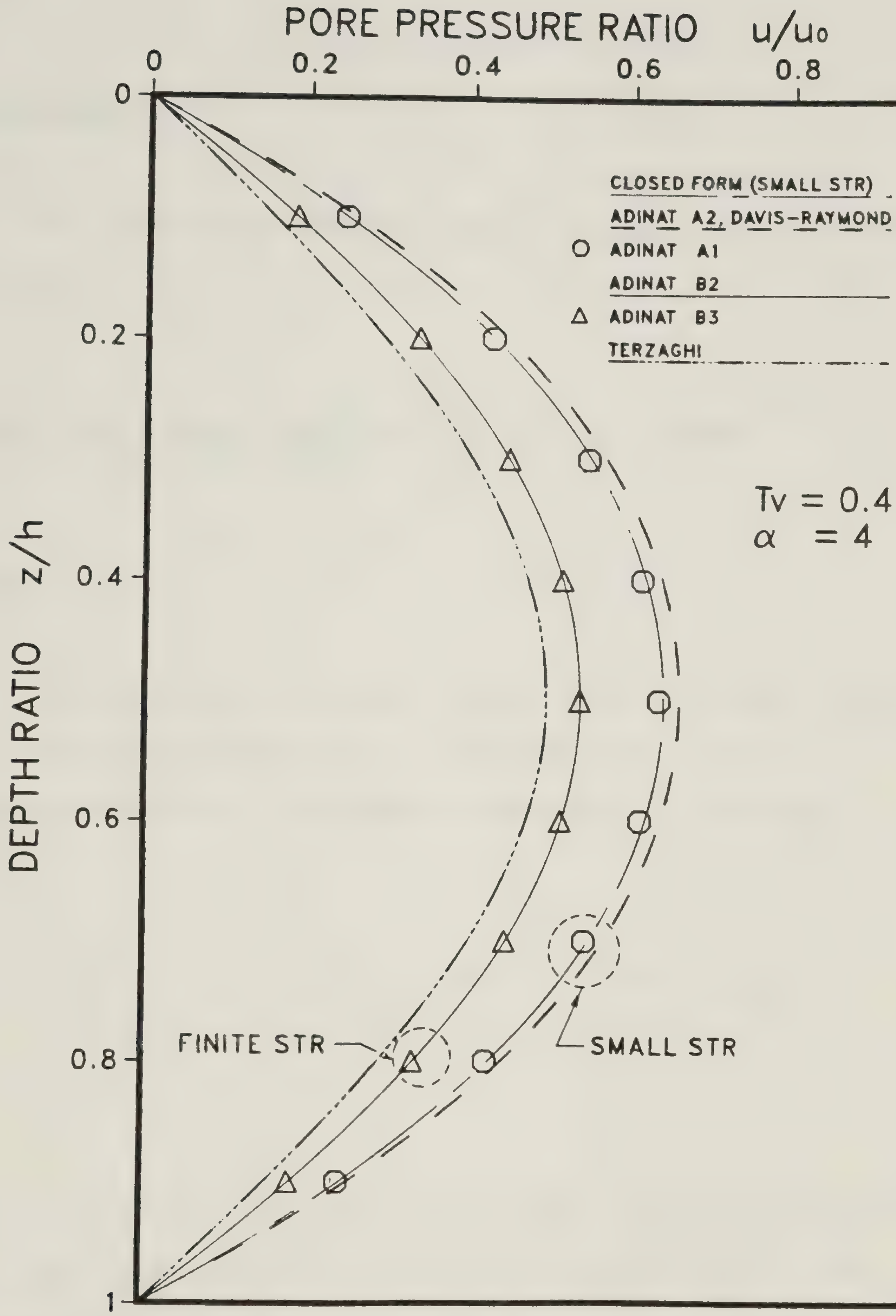


Figure 5.9 Pore pressure isochrones: thin layer analysis

5.5 Raymond Theory

Objective:

To illustrate ADINAT application to Raymond's (1966) theory.

ADINAT Nonlinear Equation: A1, A6, B7, B8, B9

Brief:

Raymond has developed a small strain theory which includes both variations in permeability and in compressibility. His general equation is given as

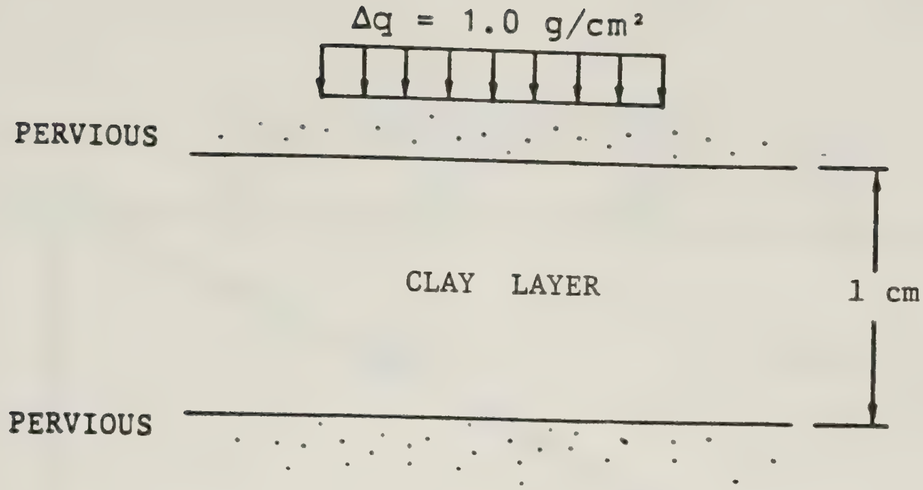
$$\frac{k_n \sigma_n'^{\nu}}{\gamma w} \left(\frac{1}{\sigma'}\right)^{\nu} \left[\frac{\nu}{\sigma'} \frac{\partial \sigma'}{\partial z} \frac{\partial u}{\partial z} - \frac{\partial^2 u}{\partial z^2} \right] = \frac{0.434\ Cc}{\sigma'(1+e_0)} \frac{\partial \sigma'}{\partial t} \tag{5.8}$$

k_n, σ_n' are constants which may equal to the initial value at the soil surface, or obtained by assuming e = 0. This equation is the same as equation *A1* with the assumed logarithmic material laws.

Description and Results:

Fig. 5.10 shows the soil profile and material properties. The loading and finite element model is given in the figure. Input data is included in Appendix A.14.

Pore pressures obtained by ADINAT using the above cited theory are shown in Fig. 5.11. Finite strain analysis is also performed and compared in the figure. Again, there is little difference between these results. This same problem is also solved by Raymond (1969) with small strain approximation and good coresspondence in the solution is noted.



COMPRESSIBILITY MODEL:

$e - \log \sigma'$

$e_o = 0.9$

$\sigma_o' = 4.0\ g/cm^2$

$Cc = 0.6$

PERMEABILITY MODEL:

$e - \log k$

$k_o = 0.01\ cm/sec$

$Ck = 0.3$

OTHER PARAMETER: $\gamma_w = 1.0\ g/cm^3$

FINITE ELEMENT MODEL FOR THE CLAY LAYER

20 EQUALLY SPACED ONE DIMENSIONAL ELEMENTS

Figure 5.10 One dimensional consolidation with logarithmic material laws

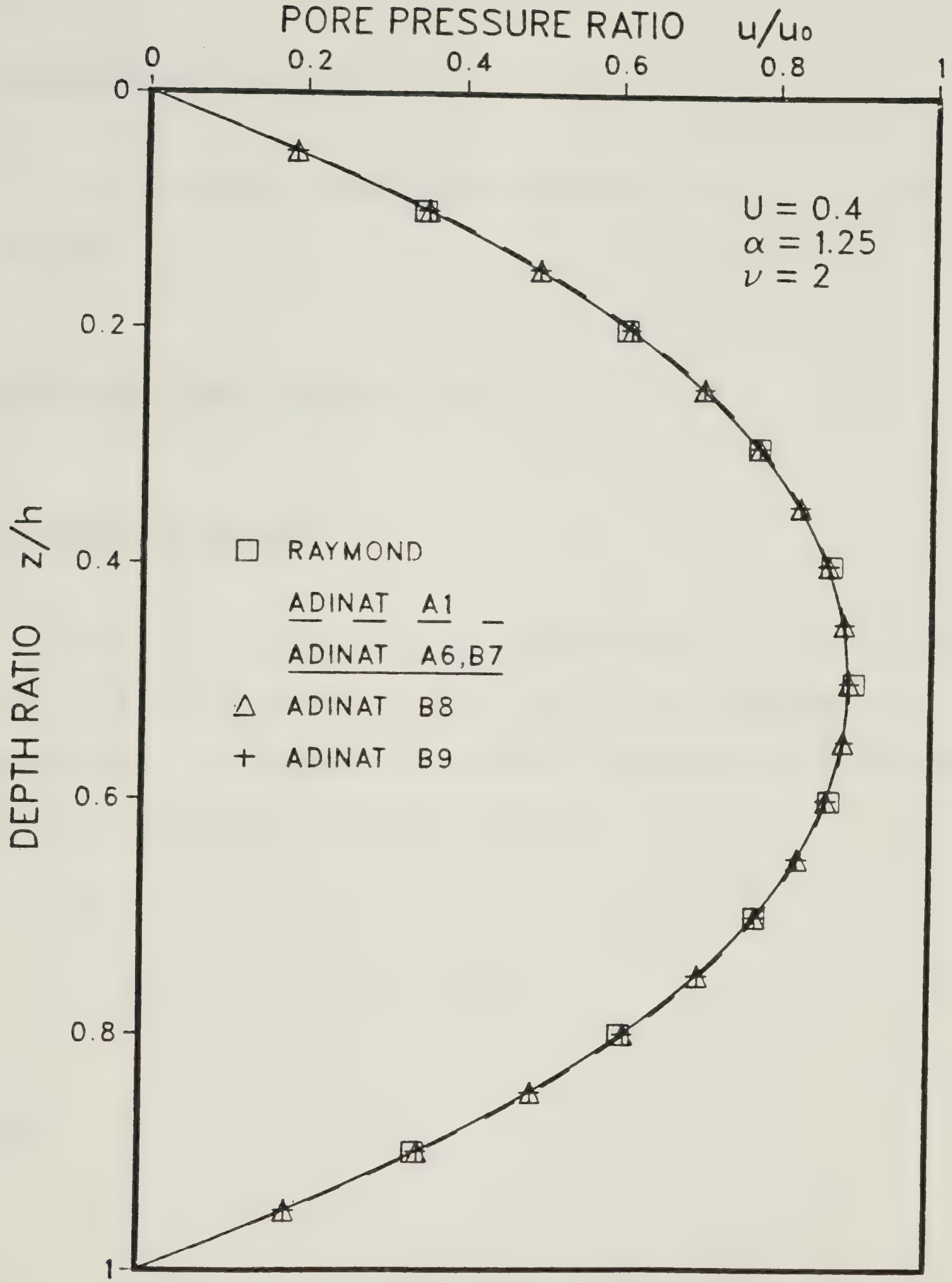


Figure 5.11 Pore pressure distribution in thin layer analysis

5.6 Poskitt Analysis

Objective:

To illustrate ADINAT application to Poskitt's (1969) analysis.

ADINAT Nonlinear Equation: B10

Analysis and Results:

Poskitt has given the same formulation as equation *B10* in Fig. 4.4. In order to make use of the given material parameters in his paper, changes of variables have been made to equation *B10* as follows. Setting

$$c = (\pi a)/h \tag{5.9}$$

and

$$\tau = (4 \cdot Cvi \cdot t)/h^2 \tag{5.10}$$

and substituting these into equation *B10*, yields:

$$\frac{\partial}{\partial c}\left[\frac{\pi^2(\alpha\beta)^{\mu}}{4(1-\mu\xi_f)}\frac{\partial\mu}{\partial c}\right] = \frac{\partial\mu}{\partial\tau} \qquad (5.11)$$

ADINAT analysis is carried out with the parameters α, β, ξ_f, Cvi/h^2 of 2, 0.37, 0.05, 1.535×10^{-4}/min respectively. Input data is in Appendix A.15. The output pore pressure at τ=0.5 is shown in Fig. 5.12.

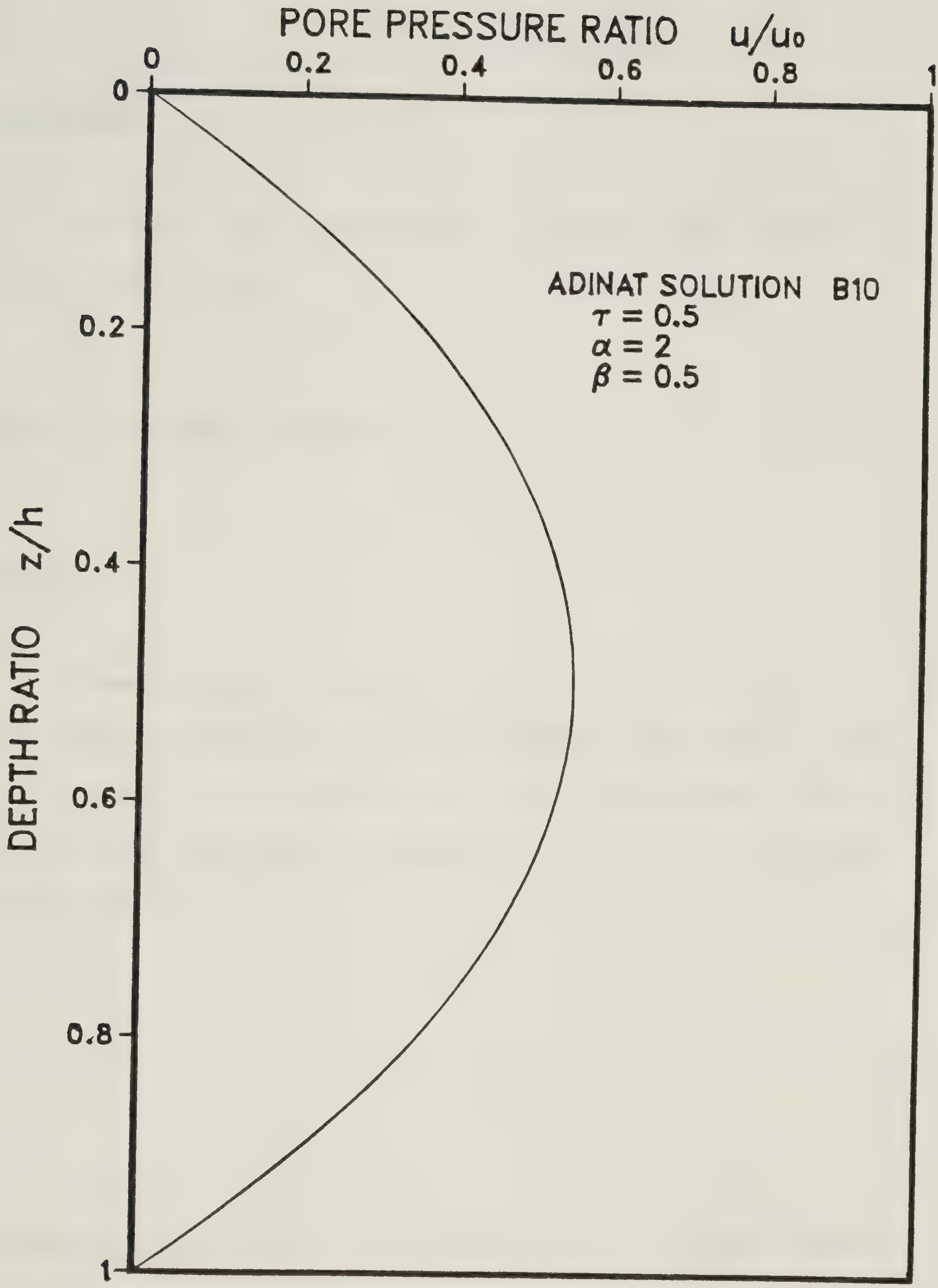


Figure 5.12 Pore pressure isochrones in finite strain - thin layer analysis

5.7 Gibson-England-Hussey General Formulation

Objective:

To verify the application of ADINAT with Gibson *et al* (1967) formulation.

ADINAT Nonlinear Equation: A7

Brief:

These authors have given a general treatment of one dimensional consolidation of a single layer soil. They arrive at a governing equation for a thin layer which is essentially identical to equation *A7*, but the variable coefficient C_F,

$$C_F = Cv\left(\frac{1+e_0}{1+e}\right)^2 \qquad (5.12)$$

is assumed either as a constant, or as a linear function of the void ratio e,

$$C_F = C_0 + \hat{m}(e-e_0) \tag{5.13}$$

C_0 and $\hat{m}$ are constants which constitute the mode of variation of C_F.

Description and Analysis

For comparing the results of Gibson *et al* and to use their given parameters, equation *A7* is tranformed into

$$\frac{\partial}{\partial a'}\left[C'_F \frac{\partial e'}{\partial a'}\right] = \frac{\partial e'}{\partial T'} \tag{5.14}$$

by changes of variables, where a' and e' are ratios of the orginal values. T' and C'_F are defined below,

$$T' = C_0 t/h \tag{5.15}$$

$$C'_F = (\lambda e'+1)/(\lambda+1) \tag{5.16}$$

in which

$$\lambda = \hat{m}e_o/(C_o-\hat{m}e_o) \tag{5.17}$$

The case of λ=0.4 and e_f/e_o=0.2 with the linear material model, Eq. 5.13, is illustrated here. The datafile is given in Appendix A.16.

Results:

ADINAT predictions for the particular case taken from Gibson *et al* is presented in Fig. 5.13. Only half of the layer is shown because of symmetry. Gibson *et al*'s results are also reproduced in the figure and good correspondence is found.

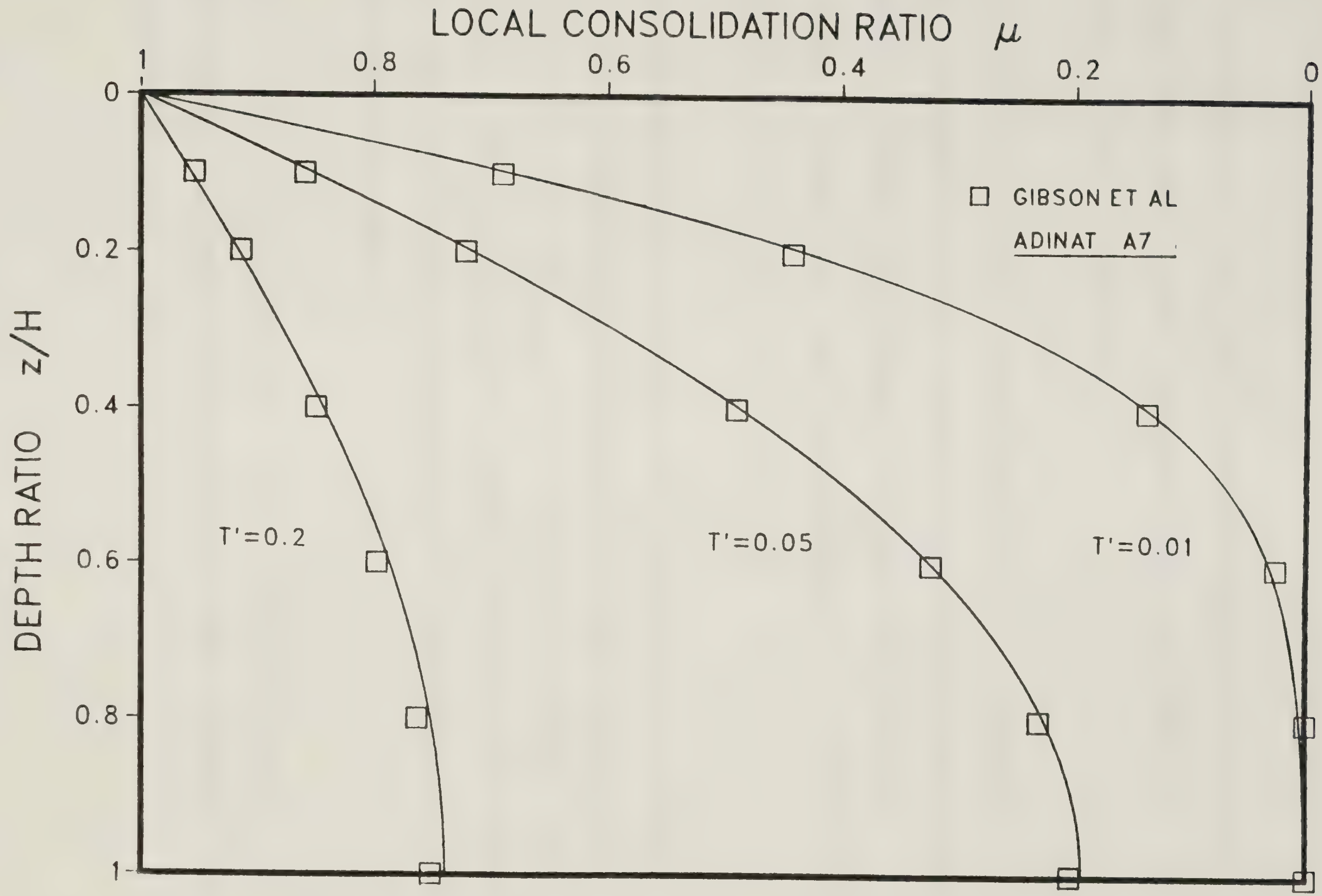


Figure 5.13 Variation of local consolidation ratio μ

5.8 Discussion

It can be seen from the preceding examples that most thin layer theories can be retrieved from the *ADINAT equations* in Fig. 4.3 and Fig. 4.4.

For cases where analytical solutions are obtained, excellent agreement can be observed with ADINAT predictions. For others in which the original work has been further approximated in some way, good correspondence is also shown between the theories and ADINAT results.

The closeness of the results of the finite strain and small strain analyses may be due to the insignificance of strain or void ratio changes in a thin layer problem. An exception to this occurs in the example of Davis and Raymond (1965), where the greater discrepancy is probably due to the larger load ratio used.

The difference between the finite strain and small strain analyses becomes more notable in deeper layers. This will be clearly seen in the next chapter.

6. NONLINEAR CONSOLIDATION ANALYSIS OF THICK SOIL LAYER BY ADINAT

6.1 General

In the following, examples are given for cases of thick layer analyses. Only a few papers on this subject can be found, probably because of the necessity of dealing with highly nonlinear equations. General descriptions, including the finite element model, given in Section 5.1, are also relevant here.

Notice that e_0 is not a constant in thick layer analysis and the initial effective stress in the Lagrangian coordinate requires

$$\sigma'(a,0) = \sigma'_\emptyset + (\gamma_s - \gamma_w) \cdot \int \frac{da}{1+e_0} \tag{6.1}$$

This expression appears much simplier in the reduced coordinate b,

$$\sigma'(b,0) = \sigma'_\emptyset + (\gamma_s - \gamma_w) \cdot b \tag{6.2}$$

The effective stress and excess pore pressure relationship at time t are given by Eq. 4.35 or Eq. 4.42, depending on the coordinate system used.

By integrating Eq. 4.40 and assuming the logarithmic effective stress - void ratio relationship, the following is obtained:

$$a = (1+e_{\emptyset})b - \frac{\sigma'_{\emptyset}\ Cc}{(\gamma_s - \gamma_w)\ \ln 10}(1 - \varsigma + \varsigma \ln \varsigma) \qquad (6.3)$$

in which

$$\varsigma = 1 + \frac{\gamma_s - \gamma w}{\sigma'_{\emptyset}} \cdot b \qquad (6.4)$$

The above expression shows the relation between the coordinate *a* and *b*, and it is useful in the thick layer analysis with the logarithmic compressibility law. Notice that the Lagrangian coordinate *a* in Eq. 6.3 can be substitued by the Eulerian coordinate *z*, in which case the same change also applies to Eq. 4.40 for computing the reduce coordinate *b*.

Several other symbols are employed in thick layer analysis. The initial void ratio at surface, $e_{\emptyset}$, can be

determined by

$$e_{\emptyset} = \frac{\gamma_s - \gamma_t}{\gamma_t - \gamma_w} \qquad (6.5)$$

The surface load ratio is computed from

$$\alpha_s = (\sigma'_{\emptyset} + \Delta q) / \sigma'_{\emptyset} \qquad (6.6)$$

and the self-weight ratio ζ is defined as

$$\zeta = [(\gamma_s - \gamma_w)\ell] / \sigma'_{\emptyset} \qquad (6.7)$$

where ℓ can be obtained from

$$\ell = \int_0^h \frac{d\Theta}{1+e(\Theta,0)} \qquad (6.8)$$

Θ represents either the coordinate a or z. A similar ratio using the average submerged weight, termed the average self-weight ratio, is expressed as

$$\bar{\zeta} = (\overline{\gamma_b} \cdot h) / \sigma'_0 \tag{6.9}$$

in which $\overline{\gamma_b}$ is the average submerged unit weight of the soil.

In applying thick layer formulations to ADINAT, the compressible stratum is divided into contiguous layers of finite depth. The expressions for material parameters are then evaluated at the mid-point of each layer. Although this is only an approximate method of the application of the thick layer formulation, good results are obtained as is shown in the following examples.

6.2 Small Strain Approximation

6.2.1 Raymond Analysis

Objective:

To illustrate the use of ADINAT in Raymond's (1969) analysis.

ADINAT Nonlinear Equation: A4

Brief:

Raymond has studied the consolidation of deep deposits in the context of small strain. Variations of permeability and compressibility are taken into account by employing logarithmic relationships. Notice that Raymond's dimensionless equation Eq. 11 used in his calculations is a further approximation of his general equation Eq. 6.

The formulation Raymond has given to solve deep deposit problems may be considered as a pseudo-thick layer analysis. The variable term $(1+e_0)$ is incorporated in the time factor to which the output time for pore pressures results are also referred. This is of little practical use because the real time may not be easily determined.

Description and Analysis:

An example is shown with the same variables assumed by Raymond. Setting

$$T = \frac{k_n' \sigma_n' \ln 10 (1+e_0)}{\gamma_w \, Cc \, h^2} t \tag{6.10}$$

and with the logarithmic material laws, gives from equation *A4*,

$$\frac{\partial}{\partial z'} \left[\sigma'^{-\nu} \frac{\partial u}{\partial z'} \right] = \frac{\sigma_\phi'^{(1-\nu)}}{\sigma'} \frac{\partial u}{\partial T} \tag{6.11}$$

where z' is the depth ratio z/h. The soil profile and material parameters for ADINAT analysis are given in Fig. 6.1. The datafile is contained in Appendix A.17.

Results:

Pore pressure distribution at 40%, 60% and 80% consolidation computed by ADINAT are compared with Raymond's solutions in Fig. 6.2. Slightly larger differences can be seen at later consolidation stages.

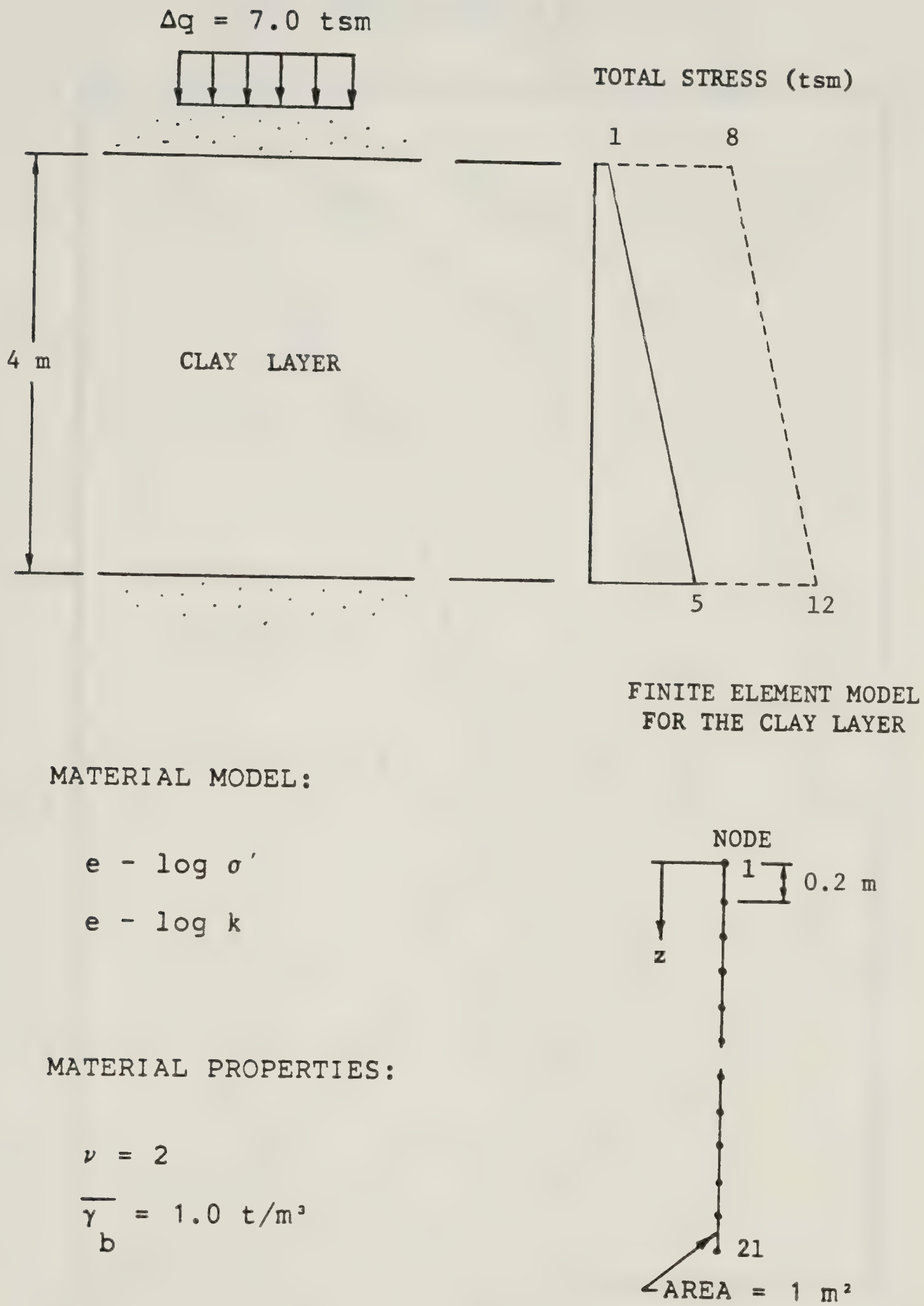


Figure 6.1 Nonlinear consolidation analysis in Raymond (1969) example

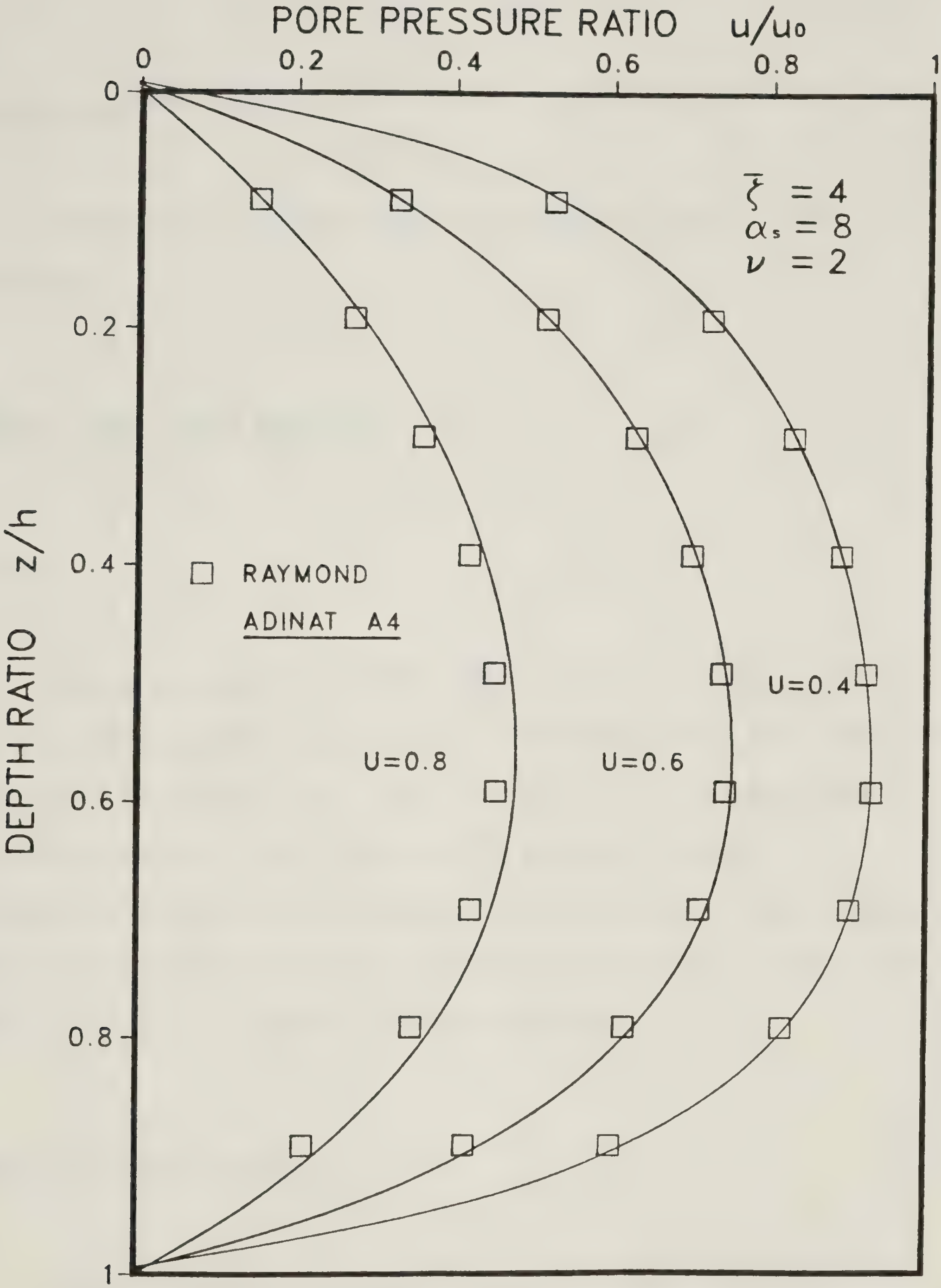


Figure 6.2 Pore pressure distribution in small strain - thick layer analysis

6.2.2 Davis Theory

Objective:

To demonstrate the use of ADINAT in Davis (1971) analysis.

ADINAT Nonlinear Equation: A4

Brief:

Davis has given a small strain theory for a thick layer. His governing equation is essentially the same as equation *A4* except that the coefficient of consolidation is assumed constant and the coefficient of volume compressibility is inversely proportional to the effective stress. Closed-form solutions are provided in some limiting cases along with these simplifications.

Analysis and Results:

Substituting the above mentioned approximations to equation *A4*, which becomes

$$\frac{\partial}{\partial z}\left[\frac{\overline{Cv}}{\sigma'} \frac{\partial u}{\partial z} \right] = \frac{1}{\sigma'} \frac{\partial u}{\partial t} \tag{6.12}$$

This equation is then used for the analysis. An example of the load ratio, α, of 1.005 and the average self-weight ratio, $\bar{\xi}$, of 5 is given in Fig. 6.3. The input datafile is in Appendix A.18. Pore pressure results at time factors 0.2 and 0.3 given by ADINAT are plotted in Fig. 6.4. Davis' closed-form solution for $\alpha_s = 1$ and Terzaghi's solutions are also compared in the figure.

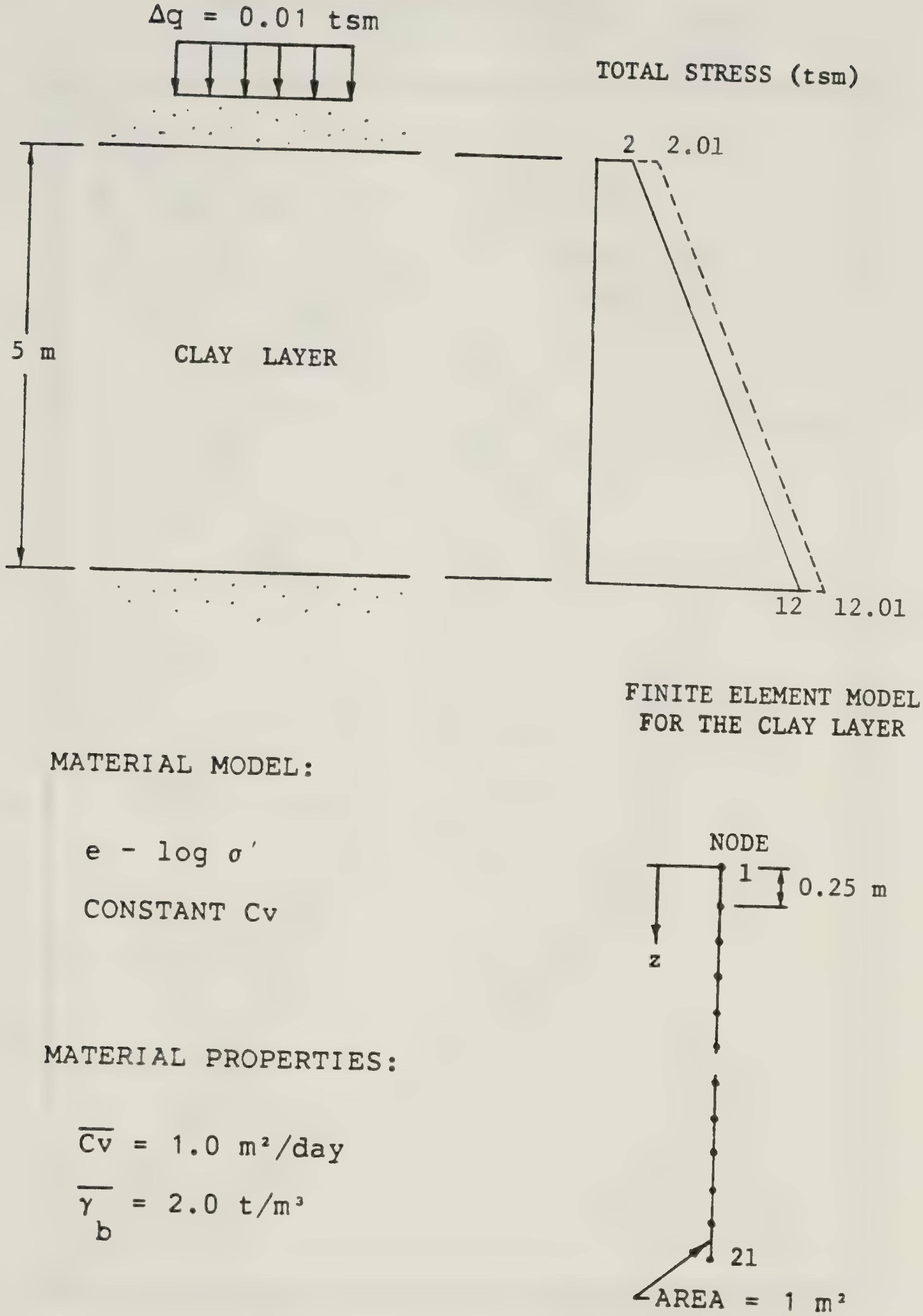


Figure 6.3 Nonlinear consolidation analysis with Davis (1971) formulation

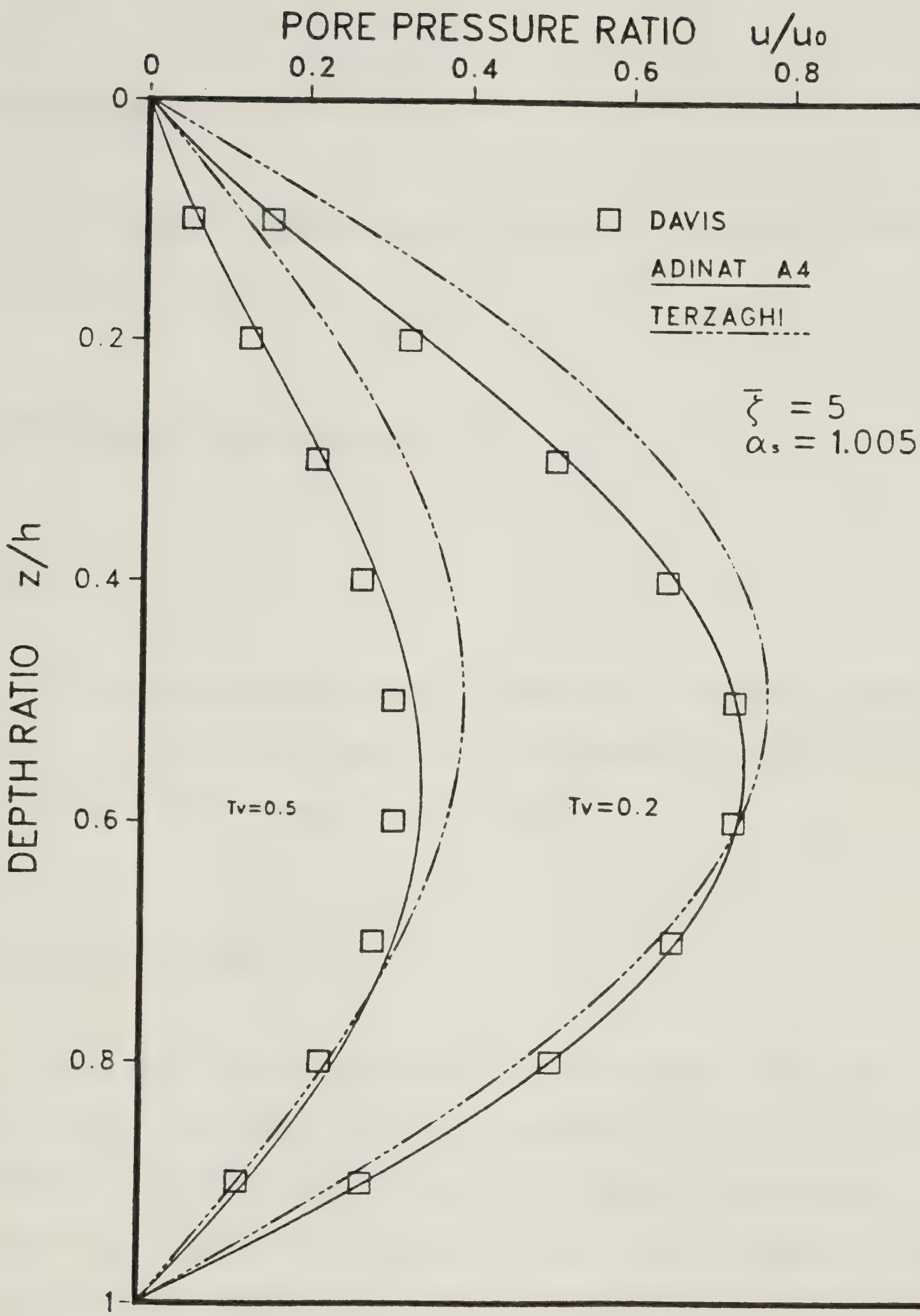


Figure 6.4 Pore pressure variation in thick layer analysis

6.2.3 Viggiani Numerical Solution

Objective:

To compare ADINAT predictions with Viggiani (1973) numerical solutions.

ADINAT Nonlinear Equation: A4

Brief:

This author has given a numerical treatment to Davis' (1971) formulation, and also considered the effects of variable load increment with depth.

Analysis and Results:

The soil layer and material parameters are shown in Fig. 6.5. The datafile is in Appendix A.19. Eq. 6.12 is used for ADINAT analysis and pore pressure results at time factor 0.2 and 0.3 are given in Fig. 6.6. Viggiani's and Terzaghi's solutions are included in the figure for comparison.

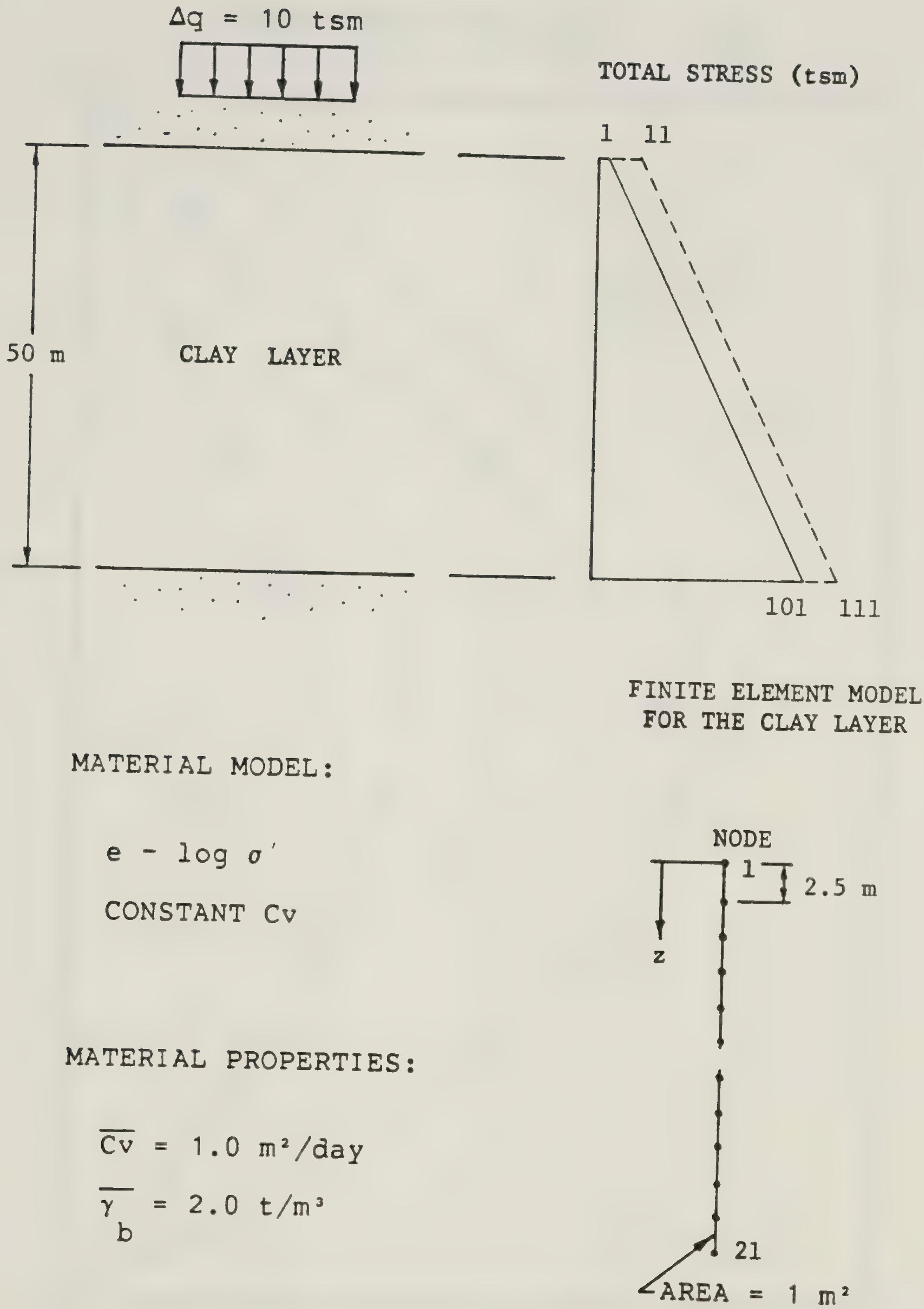


Figure 6.5 Example of nonlinear consolidation with Viggiani (1973) data

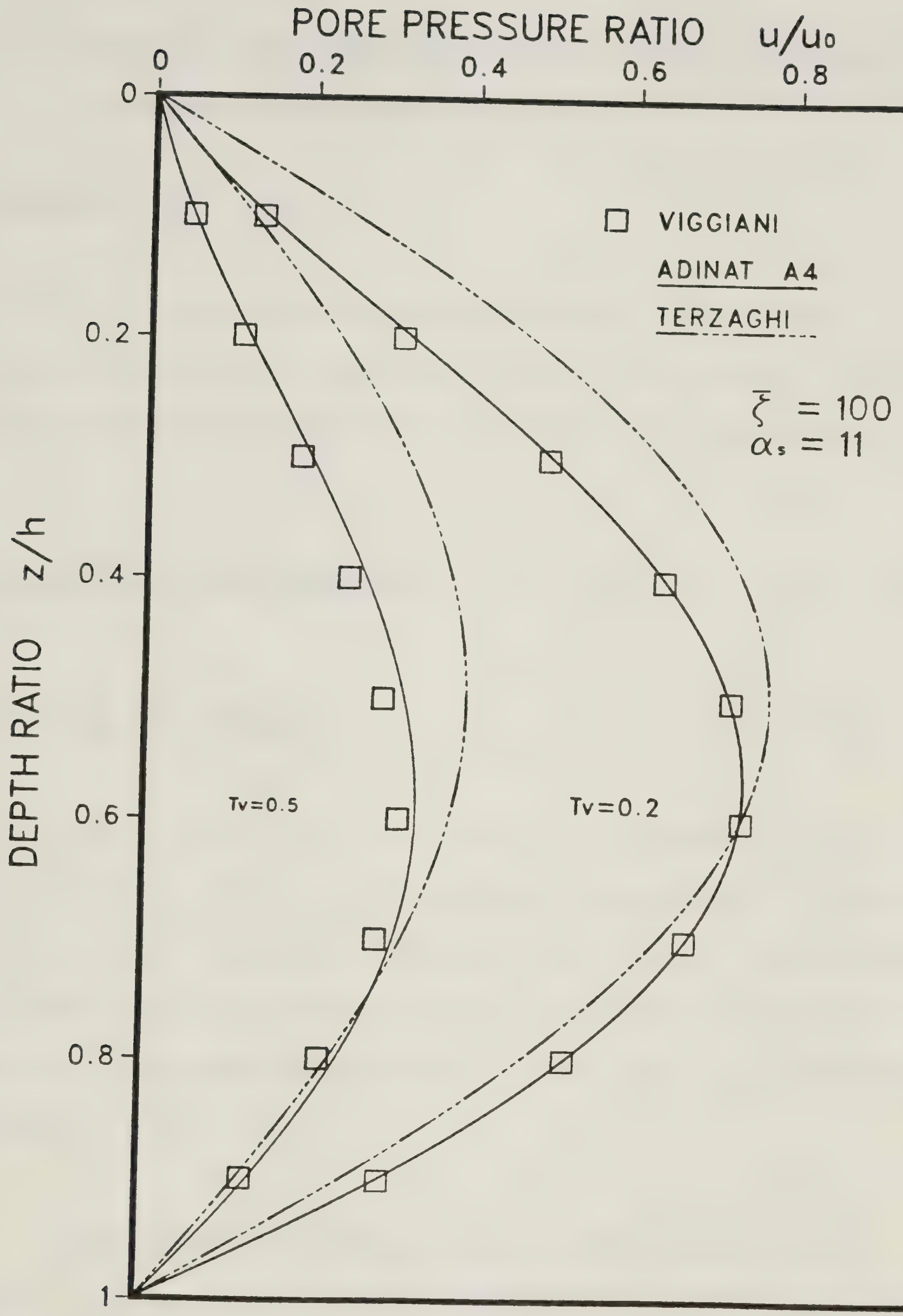


Figure 6.6 Pore pressure variation in thick layer analysis

6.3 General Analysis

6.3.1 Example with Logarithmic Material Law and Constant Coefficient of Consolidation

Objective:

To illustrate ADINAT application to nonlinear consolidation with logarithmic effective stress - void ratio relationship and constant coefficient of consolidation.

ADINAT Nonlinear Equation: A4, A8, A9

Analysis and Results:

The problem layout and material parameters are presented in Fig. 6.7. The small strain equation *A4* and both of the two finite strain - thick layer formulations, *A8* and *A9*, each of which utilizes a different coordinate system, are used for analyses. Input data can be found in Appendix A.20.

Pore pressure distributions predicted by ADINAT are shown in Fig. 6.8. Greater difference between the small strain and finite strain formulation can now be seen. Terzaghi's solution is also included in the figure.

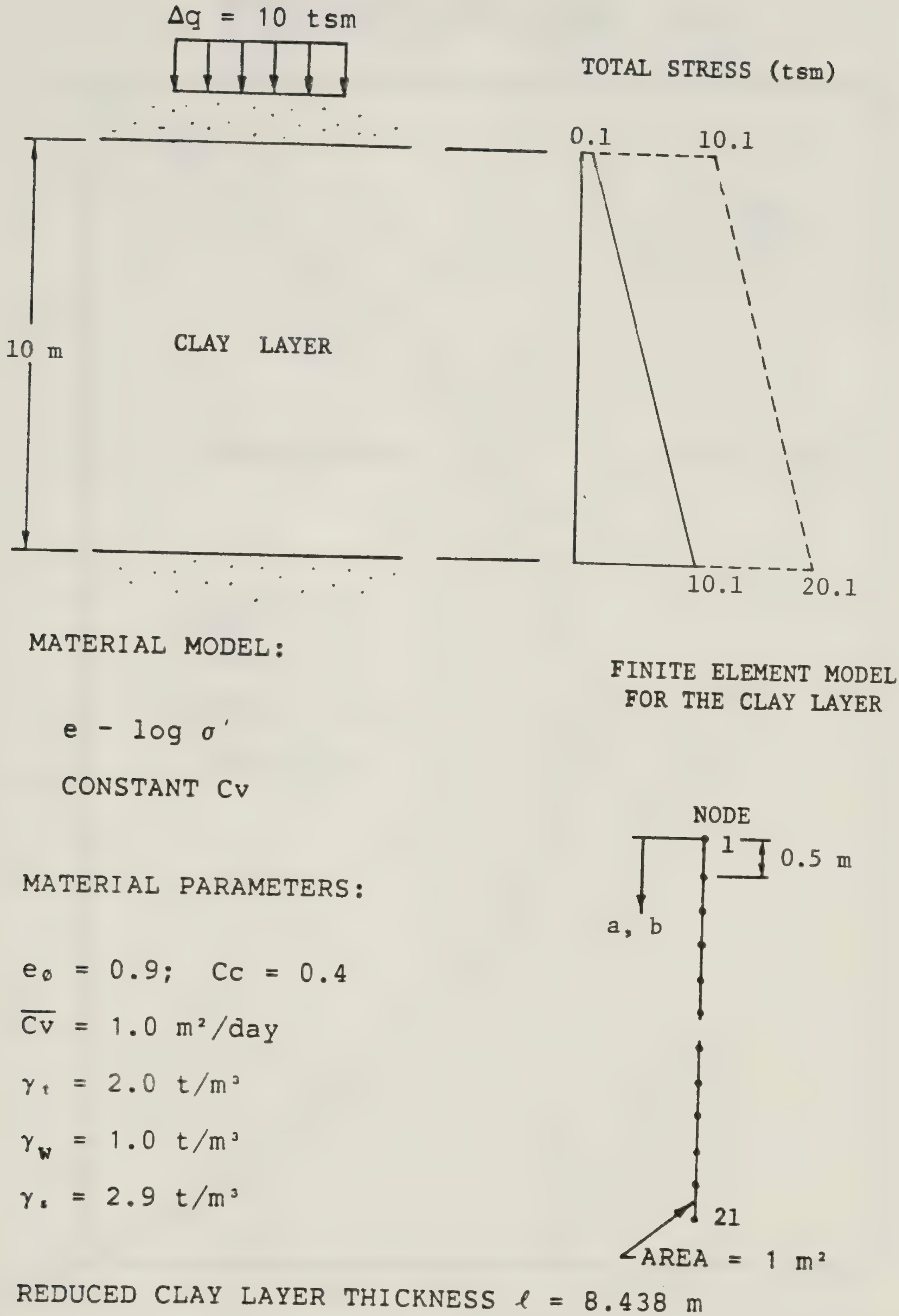


Figure 6.7 Consolidation analysis with logarithmic material law and constant coefficient of consolidation

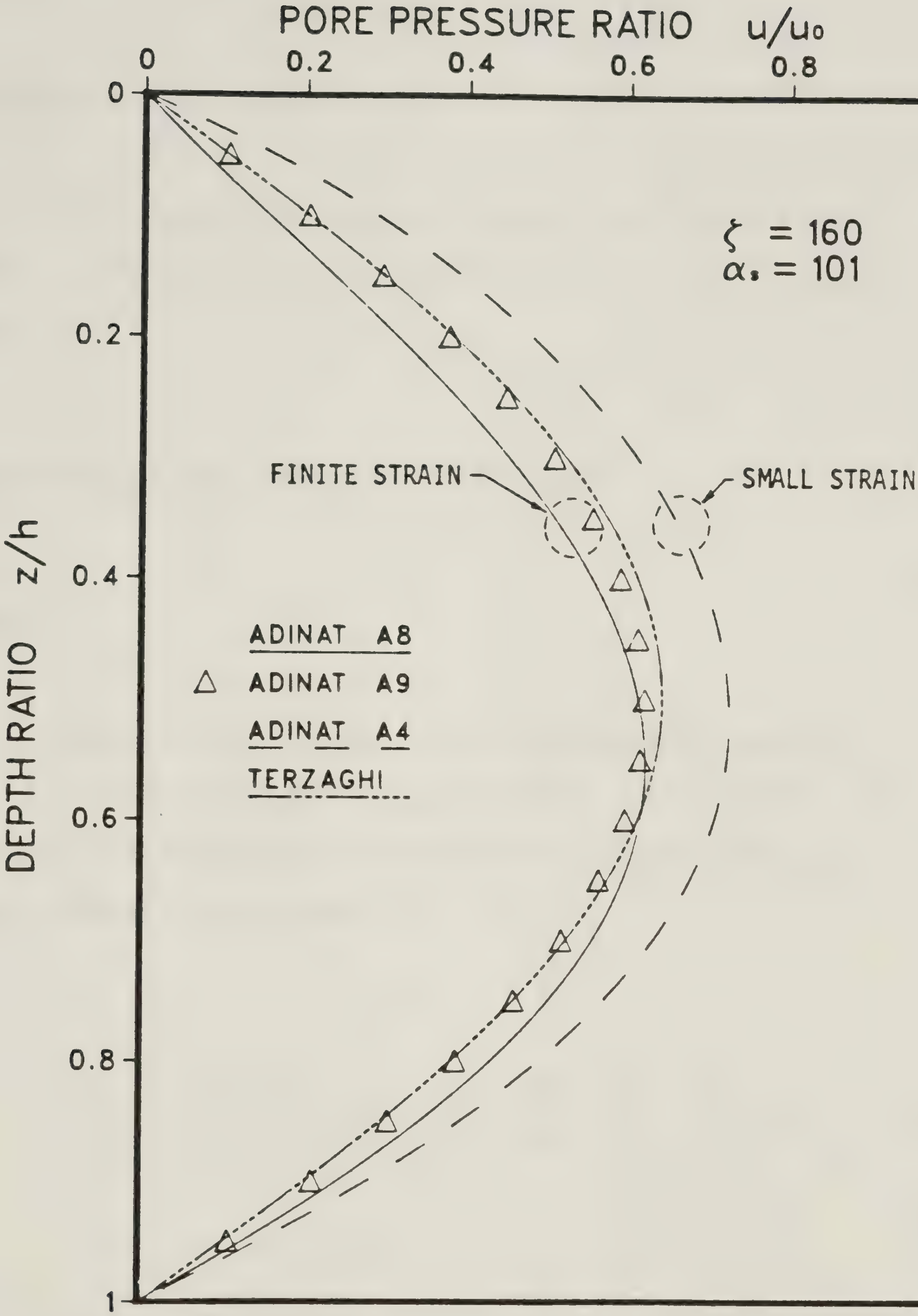


Figure 6.8 Pore pressure distribution in thick layer analysis

6.3.2 Gibson-Schiffman-Cargill General Analysis

Objective:

To illustrate the use of ADINAT in finite strain - thick layer analysis with Gibson *et al*'s (1981) general theory.

ADINAT Nonlinear Equation: A4, A8, A9

Brief:

These authors applied the same general equation, Eq. 13, from an earlier paper, Gibson *et al* (1967), but the effect of self-weight is included in their 1981 paper. Their governing equation

$$\left(1-\frac{\gamma_s}{\gamma_w}\right)\frac{d}{de}\left[\frac{k}{1+e}\right]\frac{\partial e}{\partial b} + \frac{\partial}{\partial b}\left[\frac{k}{\gamma_w(1+e)}\frac{d\sigma'}{de}\frac{\partial e}{\partial b}\right] + \frac{\partial e}{\partial t} = 0 \qquad (6.13)$$

is basically the same as equation *A9*. They made further assumptions and arrive at an approximate equation as

$$\frac{\partial^2 e}{\partial b^2} - \lambda'(\gamma_s - \gamma_w) = \frac{1}{g}\frac{\partial e}{\partial t} \tag{6.14}$$

where λ' and g are assumed constants, which may be computed as:

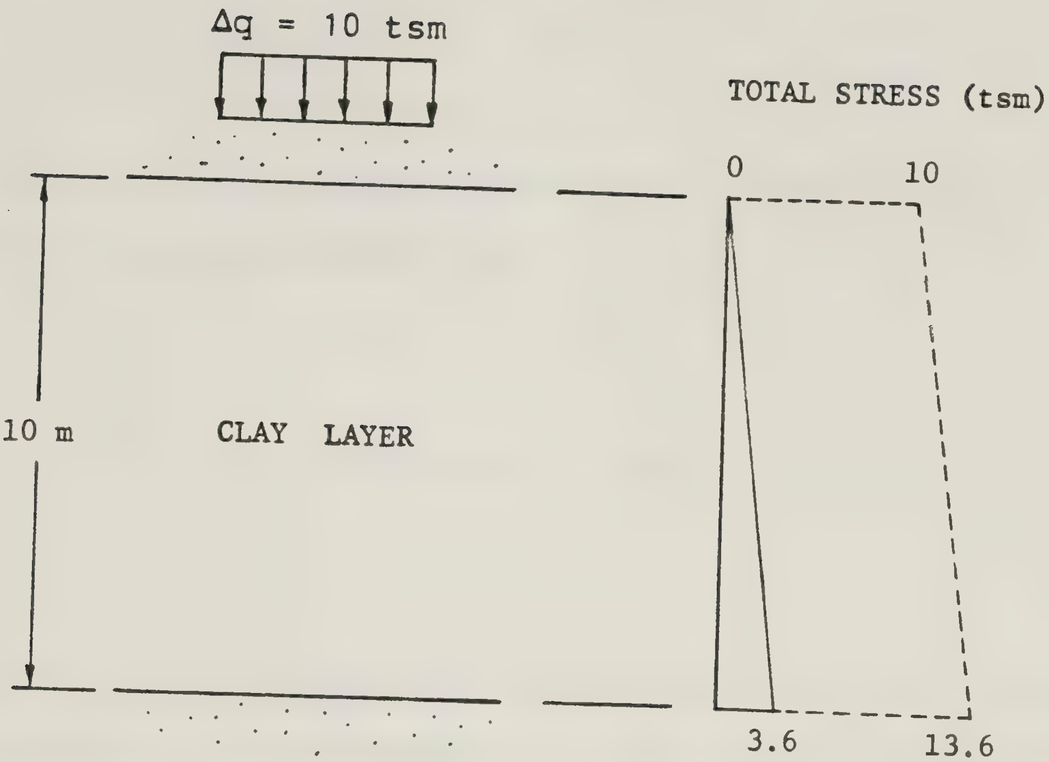
$$\lambda' = -\frac{1}{\sigma'(a)} \ln\left[\frac{e(a)-e(\infty)}{e_\emptyset - e(\infty)}\right] \tag{6.15}$$

$$g = \overline{Cv} / [1+e(a)] \tag{6.16}$$

The bracket (a) denotes the average value and (∞) refers to the final value at the layer bottom.

Description and Analysis:

The soil layout and material parameters from Gibson *et al*'s (1981) example are given in Fig. 6.9. The compressibility law employed here is the same as that in the paper:

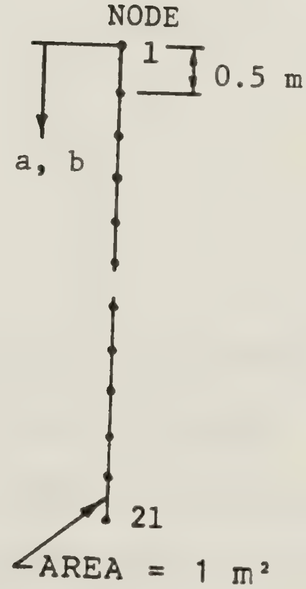


MATERIAL MODEL:

$\sigma' - \ln e$

CONSTANT Cv

FINITE ELEMENT MODEL FOR THE CLAY LAYER



MATERIAL PARAMETERS:

$e_\emptyset = 3.83; \quad e_\infty = 1.49$

$\lambda' = .332\ m^2/t$

$\overline{Cv} = .001944\ m^2/day$

$\gamma_t = 1.36\ t/m^3; \ \gamma_w = 1.0\ t/m^3$

$\gamma_s = 2.74\ t/m^3$

REDUCED CLAY LAYER THICKNESS ℓ = 2.728 m

Figure 6.9 One dimensional nonlinear consolidation with Gibson et al (1981) analysis

$$\sigma'(b,t) = -\frac{1}{\lambda'}\ln\left[\frac{e-e(\infty)}{e_\emptyset - e(\infty)}\right] \qquad (6.17)$$

The coefficient of volume compressibility can be determined with this relation and Eq. 3.8,

$$m_v = \lambda'[e-e(\infty)]/(1+e) \qquad (6.18)$$

Note that Cv is treated as a constant in the paper and hence the coefficient of permeability k can be calculated from Eq. 3.7.

Twenty solution time steps are used in this example. Datafiles are given in Appendix A.21.

Results:

Pore pressures predicted by ADINAT at two different times are shown in Fig. 6.10 and Fig. 6.11 with Gibson *et al*'s (1981) solutions. Reasonable agreement can be seen. A small strain analysis of the same problem is given in the figure. Terzaghi's solutions is also included for comparisons.

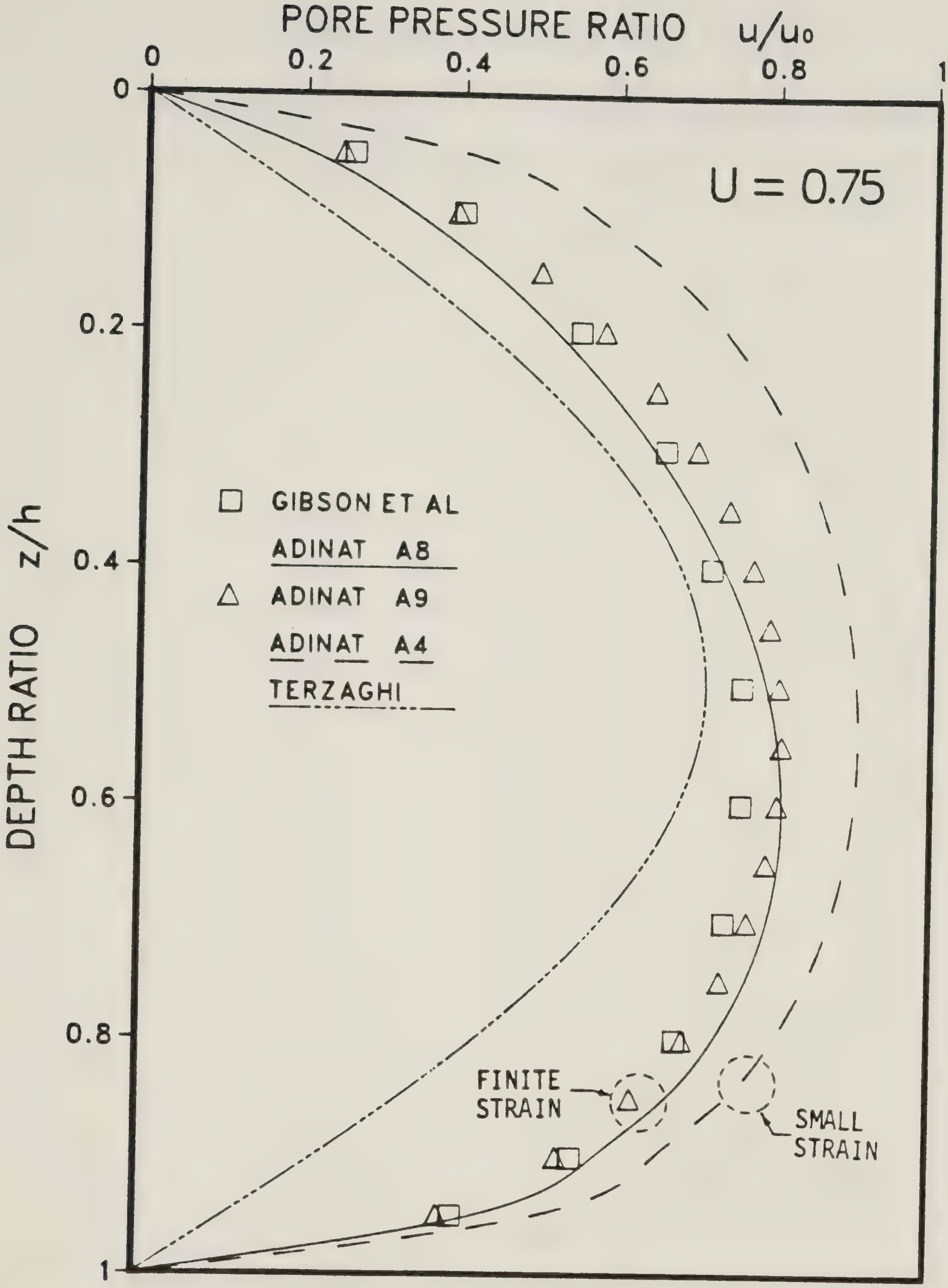


Figure 6.10 Pore pressure isochrones in thick layer analysis

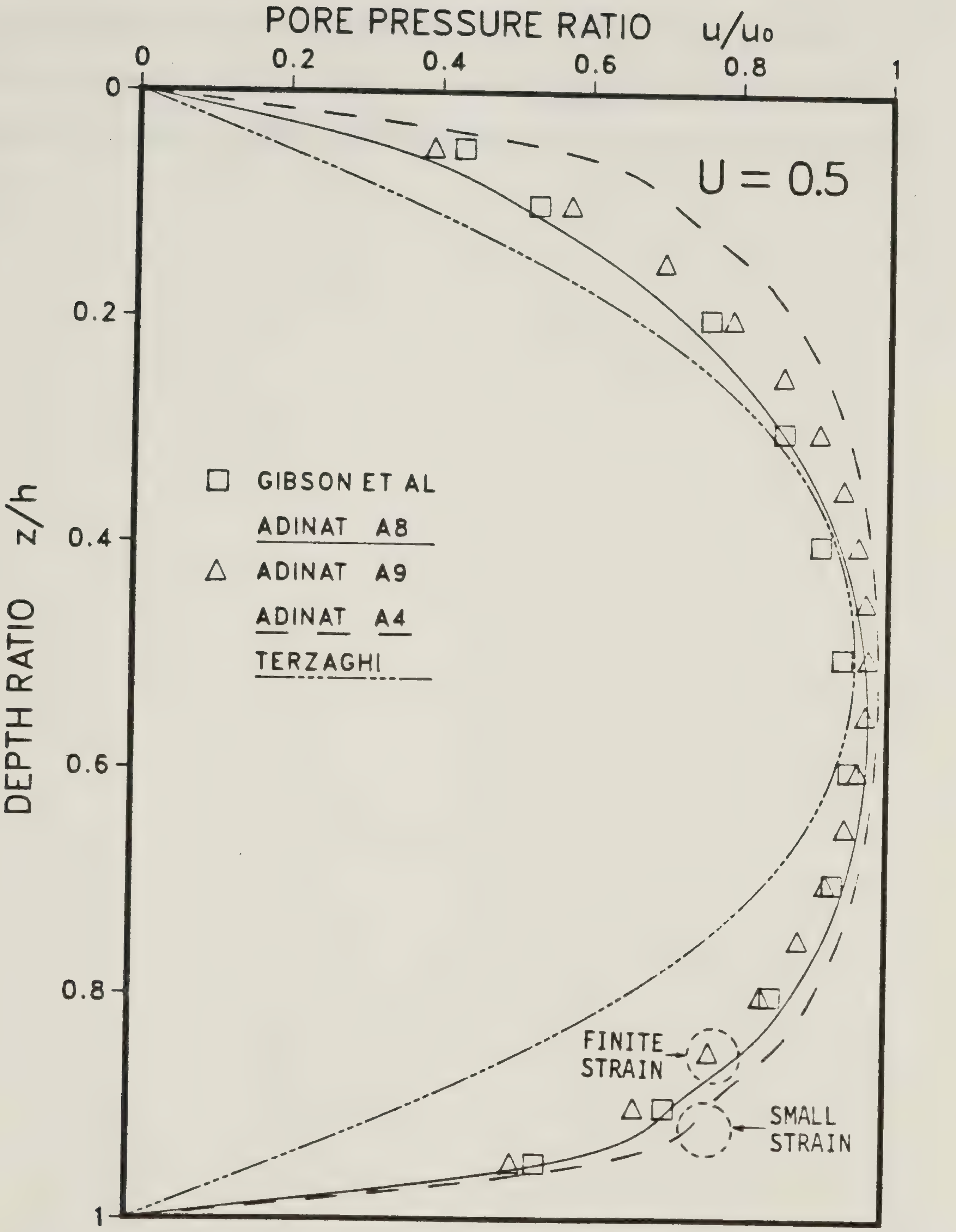


Figure 6.11 Pore pressure isochrones in thick layer analysis

It can be seen from the figures that the conventional theory is an underestimate while the small strain approximation is an overestimate of the pore pressure. Little 'bumps' on the top and bottom parts of the smooth curves are due to the limitations of the plotting machine.

6.4 Discussion

Since thick layer analysis allows for variation of effective stress with depth, and large changes of void ratio or strain, the difference between small strain and finite strain analysis becomes more significant as shown in the preceding examples. In addition, pore pressure isoschrones are all skewed because of the unsymmetrical stress distribution in the soil layer.

Note that the *average* submerged weight is used in the analyses by Raymond (1969), Davis (1971) and Viggiani (1973). Since this value does not consider the variation of void ratio throughtout the soil depth, it is apparently inadequate to take account of the self-weight effects. The theories derived by the cited authors, therefore, are only approximate to the thick layer analyses.

In the analyses of thick deposits using ADINAT, preparation of input data may become tedious since material parameters change with depth. Simple supplemental programs can be easily developed for this purpose. Examples are given in Appendix B.

7. CONCLUSIONS

Application of ADINAT to various one dimensional consolidation theories are illustrated. Within the scope of the present work, finite element solutions are readily found with simple procedures for linear and nonlinear analyses. The overall simplicity in the use of the program makes it a convenient tool for general consolidation studies. Although examples are selected from a large area of ADINAT applicability, only part of the many possible applications of the program have been shown.

The high accuracy of ADINAT and its incremental solution procedure are particularly useful in soil problems with nonlinear material behaviour. The *ADINAT equations* in Fig. 4.3 and Fig. 4.4 provide a simple means for extensive research into nonlinear consolidation behaviour.

Use of the program for nonlinear analysis is straightforward once the material relationships for a given problem is determined. These relationships are then input into the program at discrete points in the range of consolidation. Linear interpolation is carried out by ADINAT to obtain values between the input points.

If the effective stress is a function of void ratio only, there should be no great difficulty in finding their functional relationship experimentally. A series of standard consolidation tests may well be performed to accomplish this. The problem of determining permeability and void ratio relationship appears to be a little more difficult. This may possibly be resolved by additional measurements attached to the consolidation equipment.

Parametric studies can be undertaken easily by the program. Effects of load ratio, self-weight ratio, soil depth and other physical conditions can be investigated. The assistance of a small supplemental program for the preparation of input may greatly simplify the use of ADINAT for this purpose.

New sets of useful consolidation parameters for nonlinear theories may also be developed by reviewing the proposed formulations. Comprehensive experimental and case studies, however, should be performed to demonstrate the usefulness of these parameters.

The operation of ADINAT can be stopped and restarted at preselected time steps to allow for changes of input options. This restart capability may be used for analysis of problems with stress history and time dependent loading.

The program also permits the elements to be active or inactive at any specific solution time. This option may be used to simulate the physical situations for a construction period or moving boundaries.

The orthotropic material model of ADINAT can be used to analyse anisotropic conditions in soils. Variable load increment can be handled easily by the program by specifying the appropriate loading at nodal points throughout the layer.

Impeded drainage boundary conditions may be treated as layered problems with the additional top and bottom layers being assigned appropriate permeability values. Radial drainage conditions can be modeled using axisymmetric elements.

Assessment of the numerical behaviour of ADINAT, such as stability in nonlinear analyses, is required in future work. A better understanding of the numerical behaviour is essential for further development of the program. This will also facilitate program use and reduce operating costs.

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APPENDIX A

Listings of ADINAT Input Datafiles

The ADINAT program (a Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis of Temperatures) is available on the MTS system at the University of Alberta. A copy of the user's manual can be obtained from the Department of Civil Engineering. The following commands can be used to run the program

```
$RUN 3012:ADINAT  5=input  6=output
```

Listings of datafiles corresponding to the examples discussed in the thesis can be found in this appendix. The first card in each datafile contains a brief note of the file. Computer programs used for the preparation of input data of several examples are given in Appendix B.

LIST OF 'ADINAT' INPUT FILES

Datafile Page

A.1 Single homogeneous layer

```
                                             C O L U M N   N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
   1       1-D CONSOLIDATION (HOMOG, LINEAR, DOUBLE DRAIN) DATA Terzaghi-Classical
   2         11    1    0    1    1        .0   10    0
   3          1    0
   4
   5
   6
   7
   8
   9         90
  10            0.25
  11          1    1        0.        0.        0.    0
  12          2    0        0.        0.        1.    1
  13         11    1        0.        0.       10
  14          1    1
  15             1.E+0       1.E+0       1 E+0       1.E+0       1.E+0       1 E+0
  16             1.E+0       1.E+0       1 E+0
  17          1    2    0    0
  18          1    2
  19              0.        0.       50.        0
  20         1  10   0   0                                           1   1
  21          1        1.
  22              1.
  23              1.
  24          1         1    2    1    1        0
  25         10        10   11    1    0        0.
  26      STOP
------    --------------------------------------------------------------------------------
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                             C O L U M N   N U M B E R
```

```
                                             C O L U M N   N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
   1       1-D CONSOLIDATION (HOMOG, LINEAR, SINGLE DRAIN) DATA Terzaghi-Classical
   2         11    1    0    1    1        .0   10    0
   3          1    0
   4
   5
   6
   7
   8
   9         90
  10            0 25
  11          1    1        0.        0         0.    0
  12          2    0        0         0.        .5    1
  13         11    0        0.        0.        5
  14          1    1
  15             1 E+0       1 E+0       1 E+0       1.E+0       1.E+0       1 E+0
  16             1 E+0       1.E+0       1 E+0       1 E+0
  17          1    2    0    0
  18          1    2
  19              0.        0.       50         0
  20         1  10   0   0                                           1   1
  21          1        1
  22              1
  23              1
  24          1         1    2    1    1        0
  25         10        10   11    1    0        0
  26      STOP
------    --------------------------------------------------------------------------------
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                             C O L U M N   N U M B E R
```

A.2 Two layers

```
                                              C O L U M N   N U M B E R
 CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLIDATION (TWO-LAYERED, SINGLE DRAIN) DATA.Gray45
     2       21    2    0    1    3         0   15    0
     3        2    0    0
     4
     5
     6
     7
     8
     9       15   15   15
    10     61835360 247741440 309676800
    11        1    1        0.         0        0.    0
    12        2    0        0.        0.     85.25    1
    13       21    0        0.        0.      1805
    14        1    1
    15             1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
    16             1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
    17             1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
    18             1.E0        1.E0
    19        1    2
    20        1    2
    21             0        0.8500000000         0
    22       1   16                                                  1   1
    23        1         1
    24     000000025
    25           0002
    26        1         1    2    1    1
    27       16        16   17    1
    28       1   4                                                   1   1
    29        1         1
    30     .00000025
    31         .00008
    32        1        17   18    1    1
    33        4        20   21    1
    34    STOP
------    --------------------------------------------------------------------------------
 CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                              C O L U M N   N U M B E R
```

A.3 Three layers

```
                                              C O L U M N   N U M B E R
 CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLIDATION (3 LAYERS, SINGLE DRAIN) DATA Barden&Younan69
     2       25    1    0    1    1         0   10    0
     3        1    0    0
     4
     5
     6
     7
     8
     9       10    0    0
    10    1.23694E-4
    11        1    1         0         0         0    0
    12        2    0         0         0    269875    1
    13        9    0         0         0     2.159    1
    14       17    0         0         0    4.3434    1
    15       25    0         0         0    6.4262
    16        1    1
    17          1.40E14     1.40E14     1.40E14     1.40E14     1.40E14     1.40E14
    18          1.40E14     1.40E14     1.40E14     1.40E14     1.40E14     1.40E14
    19          1.40E14     1.40E14     1.40E14     1.40E14     1.40E14     1.40E14
    20          1.40E14     1.40E14     1.40E14     1.40E14
    21        1    2
    22        1    2
    23             0         0        10         0
    24       1   24                                                  1   3
    25        1         1
    26        374904
    27    5.23402E-5
    28        2         1
    29        545592
    30    4.71703E-5
    31        3         1
    32       3.13944
    33    4.47585E-5
    34        1         1    2    1    1
    35        8         8    9    1
    36        9         9   10    2    1
    37       16        16   17    2
    38       17        17   18    3    1
    39       24        24   25    3
    40    STOP
------    --------------------------------------------------------------------------------
 CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                              C O L U M N   N U M B E R
```

A.4 Four layers

```
                                      C O L U M N   N U M B E R
  CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLIDATION (4 LAYERS, DOUBLE DRAIN) DATA Schiffman&Stein70
     2       41    4    0    1    1        0    20    0
     3        2    0    0
     4
     5
     6
     7
     8
     9       20
    10           37
    11        1    1        0         0         0     0
    12        2    0        0         0         2     1
    13       40    0        0         0.       78     0
    14       41    1        0         0        80
    15        1    1
    16            1.E0        1.E0        1 E0        1 E0        1 E0        1 E0
    17            1 E0        1 E0        1.E0        1 E0        1.E0        1 E0
    18            1 E0        1 E0        1.E0        1.E0        1 E0        1 E0
    19            1 E0        1.E0        1.E0        1.E0        1.E0        1.E0
    20            1 E0        1 E0        1 E0        1.E0        1 E0        1.E0
    21            1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    22            1 E0        1.E0        1.E0
    23        1    2
    24        1    2
    25            0         0      7500         0
    26       1   5                                                    1   1
    27        1        1
    28      00000789
    29      00018187
    30        1         1    2    1    1
    31        5         5    6    1
    32       1  10                                                    1   1
    33        1        1
    34       0000234
    35       0001220
    36        1         6    7    1    1
    37       10        15   16    1
    38       1  15                                                    1   1
    39        1        1
    40      00000333
    41      00006077
    42        1        16   17    1    1
    43       15        30   31    1
    44       1  10                                                    1   1
    45        1        1
    46      00000835
    47      00012172
    48        1        31   32    1    1
    49       10        40   41    1
    50    STOP
------    --------------------------------------------------------------------------------
  CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                      C O L U M N   N U M B E R
```

A.5 Linear variation of permeability

```
                                         C O L U M N     N U M B E R
  CARD               1         2         3         4         5         6         7         8
NUMBER      12345678901234567890123456789012345678901234567890123456789012345678901234567890
------      --------------------------------------------------------------------------------
     1       1-D CONSOLIDATION (LIN K, D DR) DATA Martins65
     2         41    1    0    1    1        0    10    0
     3          2    0
     4
     5
     6
     7
     8
     9         10
    10       319.47788
    11          1    1         0         0         0    0
    12          2    0         0         0        05    1
    13         40    0         0         0      1.95    0
    14         41    1         0         0         2
    15          1    1
    16              1 E0        1 E0        1.E0        1 E0        1.E0        1.E0
    17              1 E0        1 E0        1 E0        1.E0        1.E0        1 E0
    18              1 E0        1.E0        1.E0        1 E0        1 E0        1.E0
    19              1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    20              1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    21              1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    22              1 E0        1 E0        1.E0
    23          1    2
    24          1    2
    25               0         0      3500         0
    26         1  40   0                                               1  40
    27          1         1
    28       11 875E-6
    29               1
    30          2         1
    31       15 625E-6
    32               1
    33          3         1
    34       19 375E-6
    35               1
    36          4         1
    37       23 125E-6
    38               1
    39          5         1
    40       26.875E-6
    41               1
    42          6         1
    43       30 625E-6
    44               1
    45          7         1
    46       34 375E-6
    47               1
    48          8         1
    49       38 125E-6
    50               1
    51          9         1
    52       41 875E-6
    53               1
    54         10         1
    55       45 625E-6
    56               1
    57         11         1
    58       49 375E-6
    59               1
    60         12         1
    61       53 125E-6
    62               1
    63         13         1
    64       56 875E-6
    65               1
    66         14         1
    67       60 625E-6
    68               1
    69         15         1
    70       64 375E-6
    71               1
    72         16         1
    73       68 125E-6
    74               1
    75         17         1
    76       71 875E-6
    77               1
    78         18         1
    79       75 625E-6
    80               1
    81         19         1
    82       79 375E-6
    83               1
    84         20         1
    85       83 125E-6
    86               1
    87         21         1
    88       86 875E-6
    89               1
    90         22         1
    91       90 625E-6
    92               1
    93         23         1
    94       94 375E-6
    95               1
    96         24         1
    97       98 125E-6
```

```
  98            1.
  99       25        1
 100    101.875E-6
 101            1.
 102       26        1.
 103    105.625E-6
 104            1.
 105       27        1.
 106    109.375E-6
 107            1.
 108       28        1
 109    113.125E-6
 110            1.
 111       29        1
 112    116.875E-6
 113            1
 114       30        1
 115    120.625E-6
 116            1.
 117       31        1.
 118    124.375E-6
 119            1.
 120       32        1.
 121    128.125E-6
 122            1.
 123       33        1.
 124    131.875E-6
 125            1.
 126       34        1
 127    135.625E-6
 128            1.
 129       35        1.
 130    139.375E-6
 131            1.
 132       36        1
 133    143.125E-6
 134            1.
 135       37        1.
 136    146.875E-6
 137            1.
 138       38        1.
 139    150.625E-6
 140            1.
 141       39        1.
 142    154.375E-6
 143            1.
 144       40        1.
 145    158.125E-6
 146            1.
 147        1         1    2    1
 148        2         2    3    2
 149        3         3    4    3
 150        4         4    5    4
 151        5         5    6    5
 152        6         6    7    6
 153        7         7    8    7
 154        8         8    9    8
 155        9         9   10    9
 156       10        10   11   10
 157       11        11   12   11
 158       12        12   13   12
 159       13        13   14   13
 160       14        14   15   14
 161       15        15   16   15
 162       16        16   17   16
 163       17        17   18   17
 164       18        18   19   18
 165       19        19   20   19
 166       20        20   21   20
 167       21        21   22   21
 168       22        22   23   22
 169       23        23   24   23
 170       24        24   25   24
 171       25        25   26   25
 172       26        26   27   26
 173       27        27   28   27
 174       28        28   29   28
 175       29        29   30   29
 176       30        30   31   30
 177       31        31   32   31
 178       32        32   33   32
 179       33        33   34   33
 180       34        34   35   34
 181       35        35   36   35
 182       36        36   37   36
 183       37        37   38   37
 184       38        38   39   38
 185       39        39   40   39
 186       40        40   41   40
 187    STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                          C O L U M N   N U M B E R
```

A.6 Polynomial variation of permeability

```
                                        C O L U M N    N U M B E R
  CARD               1         2         3         4         5         6         7         8
NUMBER      12345678901234567890123456789012345678901234567890123456789012345678901234567890
------      --------------------------------------------------------------------------------
     1       1-D CONSOLIDATION (POLY VAR K, D DR) DATA Schiffman&Gibson64
     2         41    1    0    1    1        0    10    0
     3          1    0
     4
     5
     6
     7
     8
     9         10
    10           7 748
    11          1    1         0         0         0    0
    12          2    0         0         0         5    1
    13         40    0         0         0      19 5    0
    14         41    1         0         0        20
    15          1    1
    16              1 E0        1 E0        1 E0        1 E0        1.E0        1 E0
    17              1.E0        1 E0        1 E0        1.E0        1 E0        1 E0
    18              1 E0        1 E0        1 E0        1 E0        1.E0        1 E0
    19              1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    20              1 E0        1.E0        1 E0        1.E0        1.E0        1 E0
    21              1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    22              1 E0        1 E0        1 E0
    23          1    2
    24          1    2
    25              0         0        500         0
    26         1  40                                                    1  40
    27          1         1
    28       904945590
    29               1
    30          2         1
    31       759613855
    32               1
    33          3         1
    34       653830050
    35               1
    36          4         1
    37       573456755
    38               1
    39          5         1
    40       510363618
    41               1
    42          6         1
    43       459546817
    44               1
    45          7         1
    46       417759873
    47               1
    48          8         1
    49       382805454
    50               1
    51          9         1
    52       353143842
    53               1
    54         10         1
    55      .327664402
    56               1
    57         11         1
    58       305546075
    59               1
    60         12         1
    61       286168922
    62               1
    63         13         1
    64       269056199
    65               1
    66         14         1
    67       253835332
    68               1
    69         15         1
    70       240210992
    71               1
    72         16         1
    73       227946094
    74               1
    75         17         1
    76       216848137
    77               1
    78         18         1
    79       206759216
    80               1
    81         19         1
    82       197548597
    83               1
    84         20         1
    85       189107123
    86               1
    87         21         1
    88       181342950
    89               1
    90         22         1
    91       174178248
    92               1
    93         23         1
    94       167546634
    95               1
    96         24         1
    97       161391147
```

```
        1
   25        1.
.155662633
        1.
   26        1
.150318459
        1.
   27        1.
.145321463
        1.
   28        1.
.140639112
        1.
   29        1.
.136242799
        1.
   30        1.
.132107271
        1.
   31        1.
.128210153
        1.
   32        1
.124531550
        1.
   33        1.
.121053713
        1.
   34        1.
.117760758
        1.
   35        1.
.114638427
        1.
   36        1.
.111673888
        1.
   37        1.
.108855558
        1.
   38        1.
.106172958
        1
   39        1
.103616582
        1.
   40        1.
.101177790
        1.
    1         1    2    1
    2         2    3    2
    3         3    4    3
    4         4    5    4
    5         5    6    5
    6         6    7    6
    7         7    8    7
    8         8    9    8
    9         9   10    9
   10        10   11   10
   11        11   12   11
   12        12   13   12
   13        13   14   13
   14        14   15   14
   15        15   16   15
   16        16   17   16
   17        17   18   17
   18        18   19   18
   19        19   20   19
   20        20   21   20
   21        21   22   21
   22        22   23   22
   23        23   24   23
   24        24   25   24
   25        25   26   25
   26        26   27   26
   27        27   28   27
   28        28   29   28
   29        29   30   29
   30        30   31   30
   31        31   32   31
   32        32   33   32
   33        33   34   33
   34        34   35   34
   35        35   36   35
   36        36   37   36
   37        37   38   37
   38        38   39   38
   39        39   40   39
   40        40   41   40
STOP
--------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
```

CARD NUMBER

C O L U M N   N U M B E R

A.7 Sinusoidal variation of permeability

```
                          C O L U M N   N U M B E R
CARD             1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
------  --------------------------------------------------------------------------------
         1-D CONSOLIDATION (SIN VAR K, D DR) DATA Schiffman&Gibson64
           41    1    D    1    1        0.   10    0
            1    0





           10
              7412
            1    1        0         0.        0.    0
            2    0        0         0.        .5    1
           40    0        0         0       19.5    0
           41    1        0         0        20
            1    1
                1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
                1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
                1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
                1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
                1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
                1.E0        1.E0        1.E0        1.E0        1.E0        1.E0
                1.E0        1.E0        1.E0
            1    2
            1    2
                0         0        50         0
           1  40                                               1  40
            1        1
        1.35333834
                1.
            2        1
        2 05783658
                 1
            3        1
        2 75581290
                1.
            4        1
        3 44286405
                 1
            5        1
        4 11505351
                 1
            6        1
        4 76793764
                1.
            7        1
        5 39759117
                 1
            8        1
        6 00013210
                 1
            9        1
        6 57184554
                 1
           10        1
        7 10920671
                 1
           11        1
        7 60890258
                 1
           12        1
        8 06785238
                 1
           13        1
        8 48322651
                 1
           14        1
        8 85246406
                 1
           15        1
        9 17328856
                 1
           16        1
        9 44372202
                 1
           17        1
        9 66209713
                 1
           18        1
        9 82706752
                 1
           19        1
        9 93761611
                 1
           20        1
        9 99306133
                 1
           21        1
        9 99306133
                 1
           22        1
        9 93761611
                 1
           23        1
        9 82706752
                 1
           24        1
        9 66209713
```

```
  98          1.
  99     25         1.
 100 9.44372202
 101          1.
 102     26         1
 103 9.17328856
 104          1.
 105     27         1
 106 8.85246406
 107          1.
 108     28         1.
 109 8.48322651
 110          1.
 111     29         1.
 112 8.06785238
 113          1.
 114     30         1.
 115 7.60890258
 116          1.
 117     31         1.
 118 7.10920671
 119          1.
 120     32         1.
 121 6.57184554
 122          1.
 123     33         1.
 124 6.00013210
 125          1.
 126     34         1
 127 5.39759117
 128          1.
 129     35         1
 130 4.76793764
 131          1.
 132     36         1.
 133 4.11505351
 134          1.
 135     37         1
 136 3.44296405
 137          1.
 138     38         1.
 139 2.75581290
 140          1.
 141     39         1.
 142 2.05783658
 143          1.
 144     40         1.
 145 1.35333834
 146          1.
 147     1         1    2    1
 148     2         2    3    2
 149     3         3    4    3
 150     4         4    5    4
 151     5         5    6    5
 152     6         6    7    6
 153     7         7    8    7
 154     8         8    9    8
 155     9         9   10    9
 156    10        10   11   10
 157    11        11   12   11
 158    12        12   13   12
 159    13        13   14   13
 160    14        14   15   14
 161    15        15   16   15
 162    16        16   17   16
 163    17        17   18   17
 164    18        18   19   18
 165    19        19   20   19
 166    20        20   21   20
 167    21        21   22   21
 168    22        22   23   22
 169    23        23   24   23
 170    24        24   25   24
 171    25        25   26   25
 172    26        26   27   26
 173    27        27   28   27
 174    28        28   29   28
 175    29        29   30   29
 176    30        30   31   30
 177    31        31   32   31
 178    32        32   33   32
 179    33        33   34   33
 180    34        34   35   34
 181    35        35   36   35
 182    36        36   37   36
 183    37        37   38   37
 184    38        38   39   38
 185    39        39   40   39
 186    40        40   41   40
 187 STOP
------ --------------------------------------------------------------------------------
 CARD           1         2         3         4         5         6         7         8
NUMBER 12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                    C O L U M N   N U M B E R
```

A.8 Linear variation of modulus of elasticity

```
                                              C O L U M N   N U M B E R
 CARD               1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
------     --------------------------------------------------------------------------------
     1      1-D CONSOLIDATION (VAR Mv, D.DR) DATA Edelmann53
     2        41    1    0    1    1        0.   10    0
     3         2    0
     4
     5
     6
     7
     8
     9        10
    10       256 1171
    11         1    1        0         0         0     0
    12         2    0        0         0    .0525    1
    13        41    0        0         0.       2 1
    14         1    1
    15             1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    16             1.E0        1 E0        1 E0        1 E0        1 E0        1.E0
    17             1 E0        1.E0        1.E0        1 E0        1 E0        1 E0
    18             1 E0        1.E0        1 E0        1 E0        1.E0        1 E0
    19             1.E0        1 E0        1 E0        1.E0        1 E0        1 E0
    20             1.E0        1 E0        1 E0        1 E0        1.E0        1 E0
    21             1 E0        1 E0        1 E0        1 E0
    22         1    2
    23         1    2
    24             0         0      3000         0
    25        1  40    0                                              1  40
    26         1        1.
    27          1.E-5
    28      156402737
    29         2        1
    30          1 E-5
    31      139251523
    32         3        1
    33          1 E-5
    34      125490196
    35         4        1
    36          1 E-5
    37      114204140
    38         5        1
    39          1.E-5
    40      104780616
    41         6        1
    42          1 E-5
    43      086793708
    44         7        1
    45          1 E-5
    46      089938168
    47         8        1
    48          1 E-5
    49      083889501
    50         9        1
    51          1 E-5
    52      078778927
    53        10        1
    54          1 E-5
    55      074177098
    56        11        1
    57          1 E-5
    58      070083224
    59        12        1
    60          1 E-5
    61      066417601
    62        13        1
    63          1 E-5
    64      063116371
    65        14        1
    66          1 E-5
    67      060127772
    68        15        1
    69          1 E-5
    70      057409401
    71        16        1
    72          1 E-5
    73      054926193
    74        17        1
    75          1 E-5
    76      052648898
    77        18        1
    78          1 E-5
    79      050552923
    80        19        1
    81          1 E-5
    82      048617442
    83        20        1
    84          1 E-5
    85     .046824700
    86        21        1
    87          1 E-5
    88      045159469
    89        22        1
    90          1 E-5
    91      043608613
    92        23        1
    93          1 E-5
    94      042160738
    95        24        1
    96          1 E-5
    97      040805917
```

```
  98     25        1.
  99       1.E-5
 100   .039535458
 101     26        1.
 102       1.E-5
 103   .038341721
 104     27        1.
 105       1.E-5
 106   .037217958
 107     28        1.
 108       1.E-5
 109   .036158192
 110     29        1.
 111       1.E-5
 112   .035157108
 113     30        1.
 114       1.E-5
 115   .034209964
 116     31        1.
 117       1.E-5
 118   .033312513
 119     32        1.
 120       1.E-5
 121   .032460945
 122     33        1.
 123       1.E-5
 124   .031651830
 125     34        1.
 126       1.E-5
 127   .030882069
 128     35        1.
 129       1.E-5
 130   .030148860
 131     36        1.
 132       1.E-5
 133   .029449659
 134     37        1.
 135       1.E-5
 136   .028782155
 137     38        1.
 138       1.E-5
 139   .028144239
 140     39        1.
 141       1.E-5
 142   .027533987
 143     40        1.
 144       1.E-5
 145   .026949638
 146      1         1    2    1
 147      2         2    3    2
 148      3         3    4    3
 149      4         4    5    4
 150      5         5    6    5
 151      6         6    7    6
 152      7         7    8    7
 153      8         8    9    8
 154      9         9   10    9
 155     10        10   11   10
 156     11        11   12   11
 157     12        12   13   12
 158     13        13   14   13
 159     14        14   15   14
 160     15        15   16   15
 161     16        16   17   16
 162     17        17   18   17
 163     18        18   19   18
 164     19        19   20   19
 165     20        20   21   20
 166     21        21   22   21
 167     22        22   23   22
 168     23        23   24   23
 169     24        24   25   24
 170     25        25   26   25
 171     26        26   27   26
 172     27        27   28   27
 173     28        28   29   28
 174     29        29   30   29
 175     30        30   31   30
 176     31        31   32   31
 177     32        32   33   32
 178     33        33   34   33
 179     34        34   35   34
 180     35        35   36   35
 181     36        36   37   36
 182     37        37   38   37
 183     38        38   39   38
 184     39        39   40   39
 185     40        40   41   40
 186   STOP
------ --------------------------------------------------------------------------------
 CARD           1         2         3         4         5         6         7         8
NUMBER 12345678901234567890123456789012345678901234567890123456789012345678901234567890
                           C O L U M N   N U M B E R
```

A.9 Sinusoidal variation of compressibility

```
                                       C O L U M N    N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
   1      1-D CONSOLIDATION (SIN VAR Mv, D DR) DATA:Schiffman&Gibson64
   2        41    1    0    1    1         0    10    0
   3         1    0
   4
   5
   6
   7
   8
   9        10
  10           4316
  11         1    1         0        0.         0    0
  12         2    0         0         0        .5    1
  13        40    0         0        0.      19 5    0
  14        41    1         0         0        20
  15         1    1
  16             1.E0        1 E0        1.E0        1 E0        1 E0        1 E0
  17             1 E0        1 E0        1.E0        1.E0        1 E0        1 E0
  18             1 E0        1 E0        1.E0        1 E0        1 E0        1 E0
  19             1 E0        1 E0        1.E0        1 E0        1 E0        1 E0
  20             1 E0        1 E0        1 E0        1 E0        1 E0        1.E0
  21             1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
  22             1.E0        1 E0        1 E0
  23         1    2
  24         1    2
  25              0         0        50         0
  26        1  40                                                    1  40
  27         1         1
  28              1
  29      964666166
  30         2         1
  31              1.
  32      894216342
  33         3         1
  34              1
  35      824418710
  36         4         1
  37              1
  38      755703595
  39         5         1
  40              1
  41     .688494649
  42         6         1
  43              1
  44      623206236
  45         7         1
  46              1
  47      560240883
  48         8         1
  49              1
  50      499986790
  51         9         1
  52              1
  53      442815446
  54        10         1
  55              1
  56      389078329
  57        11         1
  58              1
  59     .339109742
  60        12         1
  61              1
  62      293214762
  63        13         1
  64              1
  65     .251677349
  66        14         1
  67              1
  68      214753594
  69        15         1
  70              1
  71      182671144
  72        16         1
  73              1
  74      155627798
  75        17         1
  76              1
  77      133790287
  78        18         1
  79              1
  80      117293248
  81        19         1
  82              1
  83      106238389
  84        20         1
  85              1
  86     .100693867
  87        21         1
  88              1
  89      100693867
  90        22         1
  91              1
  92     .106238389
  93        23         1
  94              1
  95     .117293248
  96        24         1
  97              1
```

```
 98   .133790287
 99      25        1.
100           1.
101   .155627798
102      26        1.
103           1.
104   .182671144
105      27        1.
106           1.
107   .214753594
108      28        1.
109           1.
110   .251677349
111      29        1.
112           1.
113   .293214762
114      30        1.
115           1.
116   .339109742
117      31        1.
118           1.
119   .389079329
120      32        1.
121           1.
122    442815446
123      33        1.
124           1.
125   .499986790
126      34        1.
127           1.
128   .560240883
129      35        1.
130           1.
131   .623206236
132      36        1.
133           1.
134   .688494649
135      37        1.
136           1.
137   .755703595
138      38        1.
139           1.
140   .824418710
141      39        1.
142           1.
143   .894216342
144      40        1.
145           1.
146   .964666166
147       1         1    2    1
148       2         2    3    2
149       3         3    4    3
150       4         4    5    4
151       5         5    6    5
152       6         6    7    6
153       7         7    8    7
154       8         8    9    8
155       9         9   10    9
156      10        10   11   10
157      11        11   12   11
158      12        12   13   12
159      13        13   14   13
160      14        14   15   14
161      15        15   16   15
162      16        16   17   16
163      17        17   18   17
164      18        18   19   18
165      19        19   20   19
166      20        20   21   20
167      21        21   22   21
168      22        22   23   22
169      23        23   24   23
170      24        24   25   24
171      25        25   26   25
172      26        26   27   26
173      27        27   28   27
174      28        28   29   28
175      29        29   30   29
176      30        30   31   30
177      31        31   32   31
178      32        32   33   32
179      33        33   34   33
180      34        34   35   34
181      35        35   36   35
182      36        36   37   36
183      37        37   38   37
184      38        38   39   38
185      39        39   40   39
186      40        40   41   40
187   STOP
------ --------------------------------------------------------------------------------
 CARD           1         2         3         4         5         6         7         8
NUMBER 12345678901234567890123456789012345678901234567890123456789012345678901234567890
                            C O L U M N   N U M B E R
```

A.10 Constant coefficient of consolidation with variable permeability and compressibility

```
                                   C O L U M N   N U M B E R
  CARD            1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
     1    1-D CONSOLIDATION (VAR K,Mv CONST Cv, D DR) DATA.Schiffman&Gibson64
     2      41    1    0    1    1        0.   10    0
     3       1    0
     4
     5
     6
     7
     8
     9      10
    10         .938
    11       1    1        0.        0.         0    0
    12       2    0        0.        0         .5    1
    13      40    0        0         0       19 5    0
    14      41    1        0         0        20
    15       1    1
    16           1 E0        1.E0        1.E0        1 E0        1 E0        1.E0
    17           1 E0        1 E0        1.E0        1 E0        1 EC        1 E0
    18           1.E0        1.E0        1 E0        1 E0        1 EC        1 E0
    19           1.E0        1 E0        1.E0        1 E0        1 E0        1 E0
    20           1 E0        1 E0        1 E0        1 E0        1 E0        1 E0
    21           1 EC        1 E0        1 EC        1 E0        1 E0        1 EC
    22           1.E0        1 E0        1 E0
    23       1    2
    24       1    2
    25           0         0        50         0
    26      1  40                                                   1  40
    27       1        1
    28        90495
    29        90495
    30       2        1
    31        75961
    32        75961
    33       3        1
    34        65383
    35        65383
    36       4        1
    37        57346
    38        57346
    39       5        1
    40        51036
    41        51036
    42       6        1
    43        45955
    44        45955
    45       7        1
    46        41776
    47        41776
    48       8        1
    49        38281
    50        38281
    51       9        1
    52        35314
    53        35314
    54      10        1
    55        32766
    56        32766
    57      11        1
    58        30555
    59        30555
    60      12        1
    61        28617
    62        28617
    63      13        1
    64        26906
    65        26906
    66      14        1
    67        25384
    68        25384
    69      15        1
    70        24021
    71        24021
    72      16        1
    73        22795
    74        22795
    75      17        1
    76        21685
    77        21685
    78      18        1
    79        20676
    80        20676
    81      19        1
    82        19755
    83        19755
    84      20        1
    85        18911
    86        18911
    87      21        1
    88        18134
    89        18134
    90      22        1
    91        17418
    92        17418
    93      23        1
    94        16755
    95        16755
    96      24        1
    97        16139
```

```
  98        .16139
  99       25           1
 100        .15566
 101        .15566
 102       26           1.
 103        .15032
 104        .15032
 105       27           1.
 106        .14532
 107        .14532
 108       28           1.
 109        .14064
 110        .14064
 111       29           1.
 112        .13624
 113        .13624
 114       30           1.
 115        .13211
 116        .13211
 117       31           1.
 118        .12821
 119        .12821
 120       32           1.
 121        .12453
 122        .12453
 123       33           1.
 124        .12105
 125        .12105
 126       34           1.
 127        .11776
 128        .11776
 129       35           1.
 130        .11464
 131        .11464
 132       36           1.
 133        .11167
 134        .11167
 135       37           1.
 136        .10886
 137        .10886
 138       38           1.
 139        .10617
 140        .10617
 141       39           1.
 142        .10362
 143        .10362
 144       40           1.
 145        .10118
 146        .10118
 147        1            1    2    1
 148        2            2    3    2
 149        3            3    4    3
 150        4            4    5    4
 151        5            5    6    5
 152        6            6    7    6
 153        7            7    8    7
 154        8            8    9    8
 155        9            9   10    9
 156       10           10   11   10
 157       11           11   12   11
 158       12           12   13   12
 159       13           13   14   13
 160       14           14   15   14
 161       15           15   16   15
 162       16           16   17   16
 163       17           17   18   17
 164       18           18   19   18
 165       19           19   20   19
 166       20           20   21   20
 167       21           21   22   21
 168       22           22   23   22
 169       23           23   24   23
 170       24           24   25   24
 171       25           25   26   25
 172       26           26   27   26
 173       27           27   28   27
 174       28           28   29   28
 175       29           29   30   29
 176       30           30   31   30
 177       31           31   32   31
 178       32           32   33   32
 179       33           33   34   33
 180       34           34   35   34
 181       35           35   36   35
 182       36           36   37   36
 183       37           37   38   37
 184       38           38   39   38
 185       39           39   40   39
 186       40           40   41   40
 187    STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                               C O L U M N     N U M B E R
```

A.11 Thin layer: Samarasinghe et al (1982)

```
                                 C O L U M N   N U M B E R
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
--------------------------------------------------------------------------------
 1-D CONSOLDN (SMALL STR, THIN LYR, D.DR) DATA:Samarasinghe-etal82 EQ A1
   21    0    1    1    1        0.   10
    1    0






   10
   .000401
    1    1        0.        0.        0.    0
    2    0        0.        0. .00098552    1
   21    1        0.        0.  .0197104
    1    1
    47 88028    47 88028    47 88028    47 88028    47 88028    47 88028
    47 88028    47.88028    47.88028    47 88028    47 88028    47 88028
    47 88028    47.88028    47.88028    47.88028    47.88028    47.88028
    47.88028
    1    2    0    0
    1    2
        0         0        10.        0
   1  20   1                                               4   1  44  44
    1        1
        0.       2 4       4 8       7 2       9 6        12      14 4      16 8
      19.2      21 6       24       26 4      28 8      31 2      33 6       36
      38 4      40 8      43 2      45 6  47 88028        48.2.32918E-5  2 364E-5
2 40014E-52 43771E-52.47678E-52 51747E-52 55988E-52 60415E-5 2 6504E-52 69881E-5
2.74953E-52.80275E-5 2 8587E-52 91761E-52 97975E-53 04543E-5  3.115E-53 18887E-5
3 26749E-5 3.3514E-53 43659E-53 44122E-5
         0       2 4       4 8       7.2       9 6        12      14 4      16 8
      19.2      21 6       24       26 4      28 8      31 2      33 6       36
      38 4      40 8      43 2      45.6  47 88028        48  4.3872E-34 49998E-3
4 61871E-34 74388E-34 87602E-35 01573E-35 16369E-35 32064E-35 48743E-35 66502E-3
5 85448E-36 05706E-36 27415E-36 50739E-36 75864E-37 03007E-37.32421E-37 64404E-3
7 99308E-38 37552E-3 8 7744E-38 79639E-3
    1         1    2    1    1         0
   20        20   21    1    0         0
STOP
--------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                 C O L U M N   N U M B E R
```

```
                                 C O L U M N   N U M B E R
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
--------------------------------------------------------------------------------
 1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Samarasinghe-etal82 EQ A6
   21    0    1    1    1        0.   10
    1    0






   10
    000401
    1    1         0         0        0.    0
    2    0         0         0  00098552    1
   21    1         0         0  .0197104
    1    1
    47 88028    47 88028    47 88028    47 88028    47 88028    47 88028
    47 88028    47 88028    47 88028    47 88028    47 88028    47 88028
    47 88028    47 88028    47 88028    47 88028    47 88028    47 88028
    47 88028
    1    2    0    0
    1    2
        0         0        10         0
   1  20   1                                               4   1  44  44
    1        1
         0       2 4       4 8       7 2       9 6        12      14 4      16 8
      19 2      21 6       24.      26 4      28 8      31 2      33 6       36
      38 4      40 8      43.2      45 6  47 88028        48 2 40046E-52 43362E-5
2 46799E-52 50367E-52 54073E-52 57926E-52 61937E-52 66118E-52 70479E-52 75036E-5
2 79803E-52 84797E-52 90038E-52 95546E-53 01345E-53 07463E-5 3 1393E-53 20782E-5
3 28059E-53 35809E-53 43659E-53 44085E-5
         0       2 4       4 8       7 2       9 6        12      14 4      16 8
      19 2      21 6       24       26 4      28 8      31 2      33 6       36
      38 4      40 8      43 2      45 6  47 88028        48  4 3872E-34 49998E-3
4 61871E-34 74388E-34 87602E-35 01573E-35 16369E-35 32064E-35 48743E-35 66502E-3
5 85448E-36 05706E-36 27415E-36 50739E-36 75864E-37 03007E-37 32421E-37 64404E-3
7 99308E-38 37552E-3 8 7744E-38 79639E-3
    1         1    2    1    1         0
   20        20   21    1    0         0
STOP
--------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                 C O L U M N   N U M B E R
```

```
                                 C O L U M N   N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
     1    1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Samarasinghe-etal82  EQ:B4
     2      21    0    1    1    1        0.   10
     3       1    0
     4
     5
     6
     7
     8
     9      10
    10      .000401
    11       1    1        0.        0.        0.    0
    12       2    0        0.        0. .00098552    1
    13      21    1        0.        0.  .0197104
    14       1    1
    15       47.88028    47.88028    47.88028    47.88028    47.88028    47.88028
    16       47.88028    47.88028    47.88028    47.88028    47.88028    47.88028
    17       47.88028    47.88028    47.88028    47.88028    47.88028    47.88028
    18       47.88028
    19       1    2    0    0
    20       1    2
    21           0.        0.       10.        0.
    22      1  20   1                                               4   1  44  44
    23       1        1.
    24           0.       2.4       4.8       7.2       9.6       12.      14.4      16.8
    25         19.2      21.6       24.      26.4      28.8      31.2      33.6       36.
    26         38.4      40.8      43.2      45.6  47.88028       48.5.71374E-55.79266E-5
    27   5.87449E-5 5.9594E-56.04761E-56.13934E-56.23481E-56.33431E-56.43813E-5 6.5466E-5
    28   6.66006E-56.77894E-56.90367E-57.03478E-57.17282E-57.31844E-57.47238E-57.63547E-5
    29   7.80869E-57.99315E-58.18001E-58.19016E-5
    30           0.       2.4       4.8       7.2       9.6       12.      14.4      16.8
    31         19.2      21.6       24.      26.4      28.8      31.2      33.6       36.
    32         38.4      40.8      43.2      45.6  47.88028       48..010442713.010711161
    33   .010993776.011291708.011606238.011938793.012290968.012664551.013061555.013484256
    34   .013935231.014417415.014934164.015489333.016087371.016733444.017433582.018194866
    35   .019025672.019935982.020885425.020937778
    36       1         1    2    1    1         0.
    37      20        20   21    1    0         0.
    38   STOP
------   --------------------------------------------------------------------------------
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                 C O L U M N   N U M B E R
```

```
                                 C O L U M N   N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
     1    1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Samarasinghe-etal82  EQ:B5
     2      21    0    1    1    1        0.   10
     3       1    0
     4
     5
     6
     7
     8
     9      10
    10      .000401
    11       1    0        0.        0.        0.    1
    12      21    0        0.        0.  .0197104
    13       1    1
    14           .622        .622        .622        .622        .622        .622
    15           .622        .622        .622        .622        .622        .622
    16           .622        .622        .622        .622        .622        .622
    17           .622        .622        .622
    18       1    2    0    2
    19       1    2
    20           0.        1.       10.        1.
    21       1    1.573835201        0.
    22      21    1.573835201        0.
    23      1  20   1                                               2   1  44   0
    24       1        1.
    25         .573.573835201     .57545     .5779    .58035     .5828    .58525     .5877
    26       .59015     .5926    .59505     .5975    .59995     .6024    .60485     .6073
    27       .60975     .6122    .61465     .6171    .61955      .622.005501723.005471507
    28   .005413397.005326013.005239574.005154086.005069551.004985972.004903351 .00482169
    29    .00474099.004661251.004582475 .00450466.004427807.004351914.004276979.004203002
    30   .004129979.004057908.003986787.003916611
    31           1.
    32       1         1    2    1    1         0.
    33      20        20   21    1    0         0.
    34   STOP
------   --------------------------------------------------------------------------------
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                 C O L U M N   N U M B E R
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                                  C O L U M N   N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
    1      1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Samarasinghe-eta182  EQ:B6
    2        21    0    1    1    1         0.   10
    3         1    0
    4
    5
    6
    7
    8
    9        10
   10       .000401
   11         1    0        0.        0.        0.    1
   12        21    0        0.        0.  .0197104
   13         0    1
   14         1    2    0    2
   15         1    2
   16                 0.        1.       10.        1.
   17         1    1        1.        0.
   18        21    1        1.        0.
   19         1  20   1                                               2   1  42   0
   20         1        1.
   21                 0.       .05        .1       .15        .2       .25        .3       .35
   22                 .4       .45        .5       .55        .6       .65        .7       .75
   23                 .8       .85        .9       .95        1..003916611.003985582.004055468
   24     .004126271.004197993.004270637.004344206.004418702.004494124.004570475.004647756
   25     .004725966.004805105.004885173.004966169.005048091.005130937.005214705.005299392
   26     .005384994.005471507
   27                 1.
   28         1         1    2    1    1         0.
   29        20        20   21    1    0         0.
   30     STOP
------    --------------------------------------------------------------------------------
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                  C O L U M N   N U M B E R
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A.12 Thin layer: Barden-Berry (1965)

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                                        C O L U M N   N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
     1    1-D CONSOLDN (SMALL STR, THIN LYR, D.DR) DATA.Barden&Berry65(n=1) EQ.A1
     2      21    0    1    1    1        0.   10
     3       1    0
     4
     5
     6
     7
     8
     9      10
    10     .0055437
    11       1    1         0.        0         0.   0
    12       2    0         0.        0.  .003175    1
    13      21    1 .       0.        0      .0635
    14       1    1
    15    107 2517799 107 2517799 107 2517799 107 2517799 107 2517798 107.2517789
    16    107 2517799 107.2517799 107 2517799 107 2517799 107.2517799 107.2517799
    17    107 2517799 107.2517799 107 2517799 107.2517799 107.2517799 107.2517799
    18    107.2517799
    19       1    2    0    0
    20       1    2
    21           0         0         10        0
    22      1  20    1                                            4    1    4   46
    23       1         1
    24           0       110 2 08767E-54 22884E-5
    25           0         5         10        15        20        25        30        35
    26          40        45         50.       55        60        65        70        75
    27          80        85         90        95       100       105       110 4 05411E-3
    28   4 15087E-34 25236E-34 35893E-34 47098E-34 58895E-34.71331E-3 4 8446E-34 98341E-3
    29   5 13041E-35 28634E-35 45205E-35 62849E-35 81673E-3  6 018E-36 23369E-36 46542E-3
    30   6 71504E-36 98472E-37 27696E-37 59472E-3 7 9415E-38 32146E-3
    31       1         1    2    1    1         0
    32      20        20   21    1    0         0
    33   STOP
------   --------------------------------------------------------------------------------
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                        C O L U M N   N U M B E R
```

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                                        C O L U M N   N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
     1    1-D CONSOLDN (SMALL STR, THIN LYR, D DR) DATA Barden&Berry65(n=1/2) EQ.A1
     2      21    0    1    1    1        0.   10
     3       1    0
     4
     5
     6
     7
     8
     9      10
    10      0055437
    11       1    1         0         0         0    0
    12       2    0         0         0    003175    1
    13      21    1         0         0      0635
    14       1    1
    15    107 2517799 107 2517799 107 2517799 107 2517799 107.2517799 107 2517799
    16    107 2517799 107 2517799 107 2517799 107 2517799 107 2517799 107 2517799
    17    107 2517799 107 2517799 107 2517799 107.2517799 107 2517799 107 2517799
    18    107 2517799
    19       1    2    0    0
    20       1    2
    21           0         0         10        0
    22      1  20    1                                            4    1   46   46
    23       1         1.
    24           0         5         10        15        20        25        30        35
    25          40        45         50        55        60        65        70        75
    26          80        85         90        95       100       105       110 2 08767E-5
    27   2 53643E-52 72514E-52 86841E-52 98919E-5 3 0956E-5 3 1918E-53 28027E-53 3626'E-5
    28   3 43995E-5 3 51131E-53 58267E-53 64915E-53 71291E-53 77426E-53 83346E-53 89071E-5
    29   3 94620E-54 00006E-54 05249E-54 10353E-54 15331E-54 20192E-5
    30           0         5         10        15        20        25        30        35
    31          40        45         50        55        60        65        70        75
    32          80        85         90        95       100       105       110 4 05411E-3
    33   4 15087E-34 25236E-34 35893E-34 47098E-34 58895E-34 71331E-3 4 8446E-34 98341E-3
    34   5 13041E-35 28634E-35 45205E-35 62849E-35 81673E-3  6 018E-36 23369E-36 46542E-3
    35   6 71504E-36 98472E-37 27696E-37 59472E-3 7 9415E-38.32146E-3
    36       1         1    2    1    1         0
    37      20        20   21    1    0         0
    38   STOP
------   --------------------------------------------------------------------------------
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                        C O L U M N   N U M B E R
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                                   C O L U M N    N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLDN (SMALL STR, THIN LYR, D.DR) DATA:Barden&Berry65  EQ:A1
     2       21    1    0    1    1        .0   10    0
     3        1    0
     4
     5
     6
     7
     8
     9       10
    10      .0055437
    11        1    1        0.        0.        0.    0
    12        2    0        0.        0.   .003175    1
    13       21    1        0.        0.     .0635
    14        1    1
    15     107.2517799 107.2517799 107.2517799 107.2517799 107.2517799 107.2517799
    16     107.2517799 107.2517799 107.2517799 107.2517799 107.2517799 107.2517799
    17     107.2517799 107.2517799 107.2517799 107.2517799 107.2517799 107.2517799
    18     107.2517799
    19        1    2    0    0
    20        1    2
    21            0.        0.       50.        0.
    22       1  20   0   0                                           1   1
    23        1        1.
    24    2.08767E-5
    25    6.21763E-3
    26        1         1    2    1    1        0.
    27       20        20   21    1    0        0.
    28    STOP
------    --------------------------------------------------------------------------------
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                   C O L U M N    N U M B E R


                                   C O L U M N    N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Barden&Berry65  EQ:B1
     2       21    0    1    1    1        0.   10
     3        1    0
     4
     5
     6
     7
     8
     9       10
    10      .0055437
    11        1    1        0.        0.        0.    0
    12        2    0        0.        0.   .003175    1
    13       21    1        0.        0.     .0635
    14        1    1
    15     107.2517799 107.2517799 107.2517799 107.2517799 107.2517799 107.2517799
    16     107.2517799 107.2517799 107.2517799 107.2517799 107.2517799 107.2517799
    17     107.2517799 107.2517799 107.2517799 107.2517799 107.2517799 107.2517799
    18     107.2517799
    19        1    2    0    0
    20        1    2
    21            0.        0.       10.        0.
    22       1  20   1                                               4   1   44  44
    23        1        1.
    24            0.       5.4      10.8      16.2      21.6       27.      32.4      37.8
    25          43.2      48.6       54.      59.4      64.8      70.2      75.6       81.
    26          86.4      91.8      97.2     102.6 107.25178      108..007008442.006991599
    27    .006974399.006956825.006938858.006920477 .00690166.006882384.006862621.006842345
    28    .006821522 .00680012.006778101.006755422.006732039.006707899.006682946.006657115
    29    .006630333 .00660252.006577661 .00657358
    30            0.       5.4      10.8      16.2      21.6       27.      32.4      37.8
    31          43.2      48.6       54.      59.4      64.8      70.2      75.6       81.
    32          86.4      91.8      97.2     102.6 107.25178      108.  1.8385881.84301723
    33    1.84756236 1.85222961.85702571  1.8619581.867034431.872263681.877655251.88321952
    34    1.88896794 1.89491311.901068951.907450991.914076451.920964671.928137321.93561894
    35    1.943437331.95162424      1.9591.96021615
    36        1         1    2    1    1        0.
    37       20        20   21    1    0        0.
    38    STOP
------    --------------------------------------------------------------------------------
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                   C O L U M N    N U M B E R
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                                 C O L U M N   N U M B E R
CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
   1       1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Barden&Berry65(U=.5)  EQ:B2
   2         21    0    1    1    1        0.   10
   3          1    0
   4
   5
   6
   7
   8
   9         10
  10        .0055437
  11          1    0        0.        0.        0.    1
  12         21    0        0.        0.     .0635
  13          1    1
  14              .959        .959        .959        .959        .959        .959
  15              .959        .959        .959        .959        .959        .959
  16              .959        .959        .959        .959        .959        .959
  17              .959        .959        .959
  18          1    2    0    2
  19          1    2
  20              0.        1.       10.        1.
  21          1    1.838588002        0.    0
  22         21    1.838588002        0.
  23         1  20   1                                               2   1  44   0
  24          1        1.
  25           .8385.838588002   .844525    .85055   .856575     .8626   .868625    .87465
  26         .880675     .8867   .892725    .89875   .904775     .9108   .916825    .92285
  27         .928875     .9349   .940925    .94695   .952975      .959 .00384353.003843162
  28      .003818462.003793638.003769056.003744712.003720602.003696725.003673077.003649656
  29      .003626457.003603479.003580719.003558173 .00353584.003513717  .0034918.003470088
  30      .003448578.003427267.003406153.003385234
  31              1.
  32          1         1    2    1    1         0.
  33         20        20   21    1    0        0.
  34      STOP
------    --------------------------------------------------------------------------------
CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                 C O L U M N   N U M B E R
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                                 C O L U M N   N U M B E R
CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
   1       1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Barden&Berry65  EQ:B3
   2         21    0    1    1    1        0.   10
   3          1    0
   4
   5
   6
   7
   8
   9         10
  10        .0055437
  11          1    0        0.        0.        0.    1
  12         21    0        0.        0.     .0635
  13          0    1
  14          1    2    0    2
  15          1    2
  16              0.        1.       10.        1.
  17          1    1        1.        0.    0
  18         21    1        1.        0.
  19         1  20   1                                               2   1  42   0
  20          1        1.
  21              0.       .05        .1       .15        .2       .25        .3       .35
  22              .4       .45        .5       .55        .6       .65        .7       .75
  23              .8       .85        .9       .95        1..003385234.003406138.003427236
  24      .003448531.003470025.003491721 .00351362.003535727.003558042 .00358057.003603312
  25      .003626272.003649451.003672854.003696482 .00372034.003744429.003768752.003793314
  26      .003818116.003843162
  27              1.
  28          1         1    2    1    1         0.
  29         20        20   21    1    0        0.
  30      STOP
------    --------------------------------------------------------------------------------
CARD               1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                 C O L U M N   N U M B E R
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                                          C O L U M N    N U M B E R
  CARD              1         2         3         4         5         6         7         8
 NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
 ------    --------------------------------------------------------------------------------
      1     1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Barden&Berry65  EQ:B6
      2       21    0    1    1    1        0.   10
      3        1    0
      4
      5
      6
      7
      8
      9       10
     10       0055437
     11        1    0        0.        0.        0.    1
     12       21    0        0.        0.     .0635
     13        0    1
     14        1    2    0    2
     15        1    2
     16             0.        1.       10.         1
     17        1    1        1.        0.    0
     18       21    1        1.        0.
     19        1  20   1                                               2   1  42   0
     20        1        1.
     21             0.       .05        .1       .15        .2       .25        .3       .35
     22             .4       .45        .5       .55        .6       .65        .7       .75
     23             .8       .85        .9       .95        1..002574756.002673772.002776622
     24    .002883456.002994429.003109703.003229447.003353834.003483047.003617273 .00375671
     25    .003901561.004052038.004208362.004370761.004539474.004714748.004896841 .00508602
     26    .005282564.005486762
     27             1.
     28        1         1    2    1    1        0.
     29       20        20   21    1    0        0.
     30    STOP
 ------    --------------------------------------------------------------------------------
  CARD              1         2         3         4         5         6         7         8
 NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                          C O L U M N    N U M B E R
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A.13 Thin layer: Davis-Raymond (1965)

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                                  C O L U M N   N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
   1      1-D CONSOLDN (SMALL STR, THIN LYR, D.DR) DATA:Davis&Raymond65 EQ:A1
   2        21    0    1    1    1        0.   10
   3         1    0
   4
   5
   6
   7
   8
   9        10
  10     .005995618
  11         1    1        0.        0.        0.   0
  12         2    0        0.        0.   .001155   1
  13        21    1        0.        0.     .0231
  14         1    1
  15            562.5       562.5       562.5       562.5       562.5       562.5
  16            562.5       562.5       562.5       562.5       562.5       562.5
  17            562.5       562.5       562.5       562.5       562.5       562.5
  18            562.5
  19         1    2    0    0
  20         1    2
  21             0.        0.       10.        0.                    4   1  42   42
  22         1  20   1
  23         1        1.
  24                0      28.5       57.      85.5       114     142.5      171.     199.5
  25              228     256.5      285.     313.5      342.     370.5       399     427.5
  26             456.     484.5      513.     541.5      570.1.59599E-61.65904E-61.72727E-6
  27     1.80135E-61.88207E-61.97036E-62.06735E-62.17438E-6 2.2931E-62.42552E-62.57418E-6
  28     2.74225E-62.93381E-63.15414E-63.41024E-63.71152E-64.07141E-64.50846E-65.05062E-6
  29     5.74099E-66.64998E-6
  30                0      28.5       57.      85.5       114     142.5      171.     199.5
  31              228     256.5       285     313.5      342.     370.5      399.     427.5
  32             456.     484.5       513     541.5      570.1.79325E-31.86409E-31.94075E-3
  33     2.02399E-32.11466E-32.21389E-32.32287E-32.44312E-32.57651E-32.72531E-32.89234E-3
  34     3.08119E-33.29642E-33.54398E-33.83174E-34.17035E-34.57462E-35.05568E-35.67485E-3
  35     6.45055E-37.47188E-3
  36         1         1    2    1    1         0.
  37        20        20   21    1    0         0.
  38     STOP
------   --------------------------------------------------------------------------------
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                  C O L U M N   N U M B E R
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                                  C O L U M N   N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
------   --------------------------------------------------------------------------------
   1      1-D CONSOLDN (SMALL STR, THIN LYR, D.DR) DATA:Davis&Raymond65 EQ A2
   2        21    1    0    1    1        0.   10
   3         1    0
   4
   5
   6
   7
   8
   9        10
  10     .005995618
  11         1    0        0.        0.        0.   1
  12        21    0        0         0.     .0231
  13         1    1
  14               .9          .9          .9          .9          .9           9
  15               .9          .9          .9          .9          .9           9
  16               .9          .9          .9          .9          .9           9
  17                9          .9           9
  18         1    2    0    2
  19         1    2
  20             0.        1.       10.        1.
  21         1    1.538764005       0
  22        21    1.538764005       0                               1   1   0   0
  23         1  20   0
  24         1        1.
  25          00089
  26             1
  27         1         1    2    1    1         0
  28        20        20   21    1    0         0
  29     STOP
------   --------------------------------------------------------------------------------
 CARD             1         2         3         4         5         6         7         8
NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                  C O L U M N   N U M B E R
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                                                    C O L U M N     N U M B E R
 CARD                1         2         3         4         5         6         7         8
NUMBER      12345678901234567890123456789012345678901234567890123456789012345678901234567890
------      --------------------------------------------------------------------------------
     1       1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Davis&Raymond65  EQ:B2
     2         21    0    1    1    1        0.   10
     3          1    0
     4
     5
     6
     7
     8
     9         10
    10      .005995618
    11          1    0        0.        0.        0.    1
    12         21    0        0.        0.     .0231
    13          1    1
    14                .9          .9          .9          .9          .9          .9
    15                .9          .9          .9          .9          .9          .9
    16                .9          .9          .9          .9          .9          .9
    17                 9          .9          .9
    18          1    2    0    2
    19          1    2
    20              0.        1.       10.        1.
    21          1    1.538764005        0.
    22         21    1.538764005        0.
    23         1  20   1                                               2   1  44   0
    24          1        1.
.   25            .537.538764005       .54       .56       .58        .6       .62       .64
    26             .66       .68        .7       .72       .74       .76       .78        .8
    27             .82       .84       .86       .88        .9      .9011.36003E-31.35692E-3
    28      1.35474E-31.32023E-31.28701E-31.25504E-31.22424E-31.19456E-31.16595E-31.13836E-3
    29      1.11173E-31.08603E-3 1.0612E-31.03722E-31.01404E-39.91636E-49.69961E-4 9.4899E-4
    30      9.28691E-49.09037E-4    8.9E-48.89064E-4
    31              1.
    32          1         1    2    1    1        0.
    33         20        20   21    1    0        0.
    34      STOP
------      --------------------------------------------------------------------------------
 CARD                1         2         3         4         5         6         7         8
NUMBER      12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                                    C O L U M N     N U M B E R
```

```
                                                    C O L U M N     N U M B E R
 CARD                1         2         3         4         5         6         7         8
NUMBER      12345678901234567890123456789012345678901234567890123456789012345678901234567890
------      --------------------------------------------------------------------------------
     1       1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Davis&Raymond65  EQ:B3
     2         21    0    1    1    1        0.   10
     3          1    0
     4
     5
     6
     7
     8
     9         10
    10      .005995618
    11          1    0        0.        0.        0.    1
    12         21    0        0.        0.     .0231
    13          0    1
    14          1    2    0    2
    15          1    2
    16              0.        1.       10.        1.
    17          1    1        1.        0.
    18         21    1        1.        0.
    19         1  20   1                                               2   1  42   0
    20          1        1.
    21              0.       .05        .1       .15        .2       .25        .3       .35
    22              .4       .45        .5       .55        .6       .65        .7       .75
    23              .8       .85        .9       .95        1.    8.9E-49.07165E-49.24832E-4
    24       9.4302E-4 9.6175E-49.81044E-41.00092E-31.02141E-31.04254E-31.06433E-31.08681E-3
    25      1.11001E-31.13395E-31.15869E-31.18424E-31.21064E-31.23794E-31.26617E-31.29538E-3
    26      1.32561E-31.35692E-3
    27              1.
    28          1         1    2    1    1        0.
    29         20        20   21    1    0        0.
    30      STOP
------      --------------------------------------------------------------------------------
 CARD                1         2         3         4         5         6         7         8
NUMBER      12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                                    C O L U M N     N U M B E R
```

```
                                        C O L U M N    N U M B E R
 CARD               1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
------     --------------------------------------------------------------------------------
   1        1-D CONSOLDN (Terzaghi's Analysis, D.DR) DATA:Davis&Raymond65
   2          21    1    0    1    1        0.   10
   3           1    0
   4
   5
   6
   7
   8
   9          10
  10       .005995618
  11           1    1        0.        0.        0.    0
  12           2    0        0.        0.   .001155    1
  13          21    1        0.        0.     .0231
  14           1    1
  15              562.5       562.5       562.5       562.5       562.5       562.5
  16              562.5       562.5       562 5       562.5       562.5       562.5
  17              562.5       562.5       562.5       562.5       562.5       562.5
  18              562.5       562.5       562.5
  19           1    2    0    0
  20           1    2
  21              0.        0.       10.        0.
  22           1  20   0                                                   1    1    0    0
  23           1        1.
  24           .00089
  25               1.
  26           1         1    2    1    1         0.
  27          20        20   21    1    0         0.
  28       STOP
------     --------------------------------------------------------------------------------
 CARD               1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                        C O L U M N    N U M B E R
```

```
                                        C O L U M N    N U M B E R
 CARD               1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
------     --------------------------------------------------------------------------------
   1        1-D CONSOLDN (SMALL STR, THIN LYR, APPR:CONST Cv & e-logp, D.DR) DATA:Davis&Raymond65 EQ:Paper
   2          21    1    0    1    1        0.   10
   3           1    0
   4
   5
   6
   7
   8
   9          10
  10       .005995618
  11           1    1        0.        0.        0.    0
  12           2    0        0.        0.   .001155    1
  13          21    1        0.        0.     .0231
  14           1    1
  15       -.6020599913-.6020599913-.6020599913-.6020599913-.6020599913-.6020599913
  16       -.6020599913-.6020599913-.6020599913-.6020599913-.6020599913-.6020599913
  17       -.6020599913-.6020599913-.6020599913-.6020599913-.6020599913-.6020599913
  18       -.6020599913-.6020599913-.6020599913
  19           1    2    0    0
  20           1    2
  21              0.        0.       10.        0.
  22           1  20   0                                                   1    1    0    0
  23           1        1.
  24           .00089
  25               1.
  26           1         1    2    1    1         0.
  27          20        20   21    1    0         0.
  28       STOP
------     --------------------------------------------------------------------------------
 CARD               1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                        C O L U M N    N U M B E R
```

A.14 Thin layer: Raymond (1966, 1969)

```
                                       C O L U M N    N U M B E R
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
------  --------------------------------------------------------------------------------
     1   1-D CONSOLDN (SMALL STR, THIN LYR, APPR e-logp & e-logk, D DR) DATA Raymond66869  EQ:A1
     2     21    0    1    1    1        0.   10
     3      1    0
     4
     5
     6
     7
     8
     9     10
    10  .012425394
    11      1    1         0         0        0.    0
    12      2    0         0         0       .05    1
    13     21    1         0         0         1
    14      1    1
    15            1.          1          1.          1.          1           1
    16            1           1          1.          1.          1           1
    17            1           1          1           1           1           1
    18            1
    19      1    2    0    0
    20      1    2
    21          0          0        50         c
    22     1   20  1                                                 4   1  42  42
    23      1        1
    24           0        05         1        15         2       .25        .3        35
    25           4        45         5        55         6       .65        .7        75
    26           8        85         9        95         1      0064 006529946  00666389
    27   006801998 006944444 007091413 007243096 007399699 007561437 007728535 007901235
    28   008079788 008264463 008455542 008653326 008858131 009070295 009290173 009518144
    29  .009754611       .01
    30           0       .05         1        15        .2        25        .3        35
    31           4        45         5        55         6        65         7        75
    32           8        85         9        95         1 027429125 027706187 027988903
    33   028277449 028572005 028872263  02917992 029493683 029814267 030141896 030476806
    34   030819242  03116946  03152773 031894332 032269559  03265372.033047139 033450153
    35   033863118 034286406
    36       1         1    2    1    1         0
    37      20        20   21    1    0         0
    38  STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                       C O L U M N    N U M E E R
```

```
                                       C O L U M N    N U M B E R
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
------  --------------------------------------------------------------------------------
     1   1-D CONSOLDN (FINITE STR, THIN LYR, D DR) DATA Raymond66869  EC.A6
     2     21    0    1    1    1        0    10
     3      1    0
     4
     5
     6
     7
     8
     9     10
    10   012425394
    11      1    1         0         0         0    0
    12      2    0         0         0        05    1
    13     21    1         0         0         1
    14      1    1
    15            1           1           1           1           1           1
    16            1           1           1           1           1           1
    17            1           1           1           1           1           1
    18            1
    19      1    2    0    0
    20      1    2
    21          0          0        50         0
    22     1   20  1                                                 4   1  42  42
    23      1        1
    24           0        05         1        15         2        25         3        35
    25           4        45         5        55         6        65         7        75
    26           8        85         5        95         1 006602043 006726527 006854672
    27   006986625 007122541 007262581 007406917 007555728 007709205 007867546 008030962
    28   008199676 008373921 008553947 008740014 008932399 009131396 009337316 009550487
    29   009771258        01
    30           0        05         1        15         2        25         3        35
    31           4        45         5        55         6        65         7        75
    32           8        85         9        95         1 027429125 027706187 027988903
    33   028277449 028572005 028872263  02917992 029493683 029814267 030141896 030476806
    34   030819242  03116946  03152773 031894332 032269559  03265372 033047139 033450153
    35   033863118 034286406
    36       1         1    2    1    1         0
    37      20        20   21    1    0         0
    38  STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                       C O L U M N    N U M B E R
```

```
                                          C O L U M N   N U M B E R
  CARD             1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Raymond66&69   EQ:B7
     2       21    0    1    1    1        0.   10
     3        1   .0
     4
     5
     6
     7
     8
     9       10
    10    .012425394
    11        1    1        0.        0.        0.   0
    12        2    0        0.        0.       .05    1
    13       21    1        0.        0.        1.
    14        1    1
    15              1.          1.          1.          1.          1.          1.
    16              1.          1.          1.          1.          1.          1.
    17              1.          1.          1.          1.          1.          1.
    18              1.
    19        1    2    0    0
    20        1    2
    21            0.        0.       50.        0.
    22       1  20   1                                               4   1  42  42
    23        1        1.
    24            0.       .05        .1       .15        .2       .25        .3       .35
    25            .4       .45        .5       .55        .6       .65        .7       .75
    26            .8       .85        .9       .95        1..048138928.049046605.049980977
    27    .050943115.051934145 .05295525.054007678  05509274.056211816 057366363.058557917
    28    .059788096.061058611.062371269.063727979.065130761.066581753.068083219.069637558
    29    .071247317.072915195
    30            0.       .05        .1       .15        .2       .25        .3       .35
    31            .4       .45        .5       .55        .6       .65        .7       .75
    32            .8       .85        .9       .95        1.        .2.202020202.204081633
    33    .206185567.208333333.210526316.212765957.215053763.217391304 .21978022.222222222
    34    .224719101.227272727.229885058 .23255814.235294118.238095238.240963855.243902439
    35     .24691358       .25
    36        1         1    2    1    1        0.
    37       20        20   21    1    0        0.
    38    STOP
------    --------------------------------------------------------------------------------
  CARD             1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                          C O L U M N   N U M B E R
```

```
                                          C O L U M N   N U M B E R
  CARD             1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Raymond66&69   EQ:B8
     2       21    0    1    1    1        0.   10
     3        1    0
     4
     5
     6
     7
     8
     9       10
    10    .012425394
    11        1    0        0.        0.        0.   1
    12       21    0        0.        1.
    13        1    1
    14              .9          .9          .9          .9          .9          .9
    15              .9          .9          .9          .9          .9          .9
    16              .9          .9          .9          .9          .9          .9
    17              .9          .9          .9
    18        1    2    0    2
    19        1    2
    20            0.        1.       50.        1.
    21        1    1.841853992        0.   0
    22       21    1.841853992        0.
    23       1  20   1                                               2   1  44   0
    24        1        1.
    25           .84.841853992      .843      .846      .849      .852      .855      .858
    26          .861      .864      .867       .87      .873      .876      .879      .882
    27          .885      .888      .891      .894      .897        .9.239228991 .24069464
    28    .241605211.244005679.246430649.248880373.251355109.253855117.256380658.258931999
    29    .261509406 .26411315.266743506.269400748.272085158.274797016.277536609.280304224
    30    .283100152.285924689.288778131.291660779
    31            1.
    32        1         1    2    1    1        0.
    33       20        20   21    1    0        0.
    34    STOP
------    --------------------------------------------------------------------------------
  CARD             1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                          C O L U M N   N U M B E R
```

```
                                     C O L U M N   N U M B E R
  CARD             1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA:Raymond66869  EQ:B9
     2       21    0    1    1    1        0.   10
     3        1    0
     4
     5
     6
     7
     8
     9       10
    10    .012425394
    11        1    0        0.        0.        0.    1
    12       21    0        0.        0.        1.
    13        0    1
    14        1    2    0    2
    15        1    2
    16            0.        1.       50.        1
    17        1    1        1.        0.    0
    18       21    1        1.        0.
    19       1  20   1                                               2   1  42   0
    20        1        1
    21            0.       .05        .1       .15        .2       .25        .3       .35
    22            .4       .45        .5       .55        .6       .65        .7       .75
    23            .8       .85        .9       .95        1..291660778.288866765 .28610019
    24    .283360778.280648259.277962366.275302831.272669394.270061793.267479771.264923073
    25    .262391446.259884642.257402412.254944512  .2525107.250100735.247714381.245351402
    26    .243011565 .24069464
    27            1.
    28        1         1    2    1    1         0.
    29       20        20   21    1    0         0.
    30    STOP
------    --------------------------------------------------------------------------------
  CARD             1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                     C O L U M N   N U M B E R
```

A.15 Finite strain-thin layer: Poskitt (1969)

```
                                      C O L U M N    N U M B E R
 CARD               1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
------     --------------------------------------------------------------------------------
     1      1-D CONSOLDN (FINITE STR, THIN LYR, D.DR) DATA Poskitt69 EQ B10
     2        21    0    1    1    1        0.   10
     3         1    0
     4
     5
     6
     7
     8
     9        10
    10            .05
    11         1    0        0.        0.        0.    1
    12        21    0        0         0 3.14159265
    13         0    1
    14         1    2    0    2
    15         1    2
    16             0         1.       50.        1
    17         1    1        1         0     0
    18        21    1        1.        0
    19        1  20   1                                               2   1  42   0
    20         1        1
    21           0 0       0 05      0 10      0 15      0 20      0 25      0 30      0 35
    22           0 40      0 45      0 50      0 55      0 60      0 65      0 70      0 75
    23           0 80      0 85      0 90      0 95      1 002 467401102 435758182 40651093
    24     2 376654142 347182672 318091442 289375442 261029742 233049452 205429772 17816596
    25     2 151253322 124687262 058463192 072576642 047023172 021798391.995897981.97231770
    26     1 948053331 92410073
    27             1
    28         1         1    2    1    1        0
    29        20        20   21    1    0        0
    30     STOP
------     --------------------------------------------------------------------------------
 CARD               1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                      C O L U M N    N U M B E R
```

A.16 Finite strain-thin layer: Gibson et al (1967)

```
                                     C O L U M N   N U M B E R
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
------  --------------------------------------------------------------------------------
     1   1-D CONSOLDN (FINITE STR, THIN LYR, APPR:LIN Cf, D.DR) DATA:Gibson-etal67 EQ:A7
     2     41    0    1    1    1        0.   20    0
     3      1    0    0
     4
     5
     6
     7      1    0
     8      1   21
     9     20
    10       .0005
    11      1    0        0.        0.        0.    1
    12     41    0        0.        0.        1.
    13      1    1
    14            1.          1.          1.          1.          1.          1.
    15            1.          1.          1.          1.          1.          1.
    16            1.          1.          1.          1.          1.          1.
    17            1.          1.          1.          1.          1.          1
    18            1.          1.          1.          1.          1.          1.
    19            1.          1.          1.          1.          1.          1.
    20            1.          1.          1.          1.          1
    21      1    2    0    2    0    0
    22      1    2
    23          0.        1.       10.        1.
    24      1    1       0.2        0.    0
    25     41    1       0.2        0
    26     1  40   1   0                                           2   1   4
    27      1        1.
    28          0.        1.57142857141.14285714
    29          1.
    30      1    0    1    2    1    1         0
    31     40    0   40   41    1    0        0.
    32  STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                     C O L U M N   N U M B E R
```

A.17 Small strain-thick layer: Raymond (1969)

```
                                    C O L U M N    N U M B E R
  CARD            1         2         3         4         5         6         7         8
 NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
 ------  --------------------------------------------------------------------------------
      1   1-D CONSOLDN (SMALL STR, THICK LYR, APPR:e-logp & e-logk, D.DR) DATA:Raymond69 EO:A4
      2     21    0    1    1    1         0.   10
      3      1    0
      4
      5
      6
      7
      8
      9    10
     10    .038575
     11      1    1         0.        0.        0.    0
     12      2    0         0.        0.       .05    1
     13     21    1         0.        0.        1.
     14      1    1
     15            7.        7.        7.        7.        7.        7.
     16            7.        7.        7.        7.        7.        7.
     17            7.        7.        7.        7.        7.        7.
     18            7.
     19      1    2    0    0
     20      1    2
     21           0.        0.       10         0
     22     1  20    1                                        4  20  42  42
     23      1         1.
     24        0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
     25      2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
     26      5.600     5.950     6.300     6.650     7.000.015241579 .016649324 .018261505
     27  .020119712 .022276676 .024800050 .027777778.031325867 .035599858 .040812162 .047258979
     28  .055363322 .065746220 .078348335 .097656250.123114805.160000000.216333153 .308641975
     29  .475624257.826446281
     30        0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
     31      2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
     32      5.600     5.950     6.300     6.650     7.000 .123456790 .129032258 .135135135
     33  .141843972 .149253731 .157480315 .166666667.176991150 .188679245 .202020202.217391304
     34  .235294118.256410256 .281690141.312500000 .350877193.400000000.465116279.555555556
     35  .689655172.909090909
     36      2         1.
     37        0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
     38      2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
     39      5.600     5.950     6.300     6.650     7.000 .014515895 .015822159 .017313019
     40  .019024970 .021003991 .023308665 .026014568 .029220542 .033057851.037703836 .043402778
     41  .050498674.059488400 .071111111.086505190 .107497984.137174211.181077411.250000000
     42  .367309458.591715976
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     44      2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
     45      5.600     5.950     6.300     6.650     7.000.120481928 .125786164 .131578947
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     57      2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
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     94  .166597251.226757370
     95        0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
     96      2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
     97      5.600     5.950     6.300     6.650     7.000 .109890110 .114285714 .119047619
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     5.600     5.950     6.300     6.650     7.000.010628122.011438703.012345679
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208        5.600     5.950     6.300     6.650     7.000.008416800.008984524.009611688
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218       16         1.
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221        5.600     5.950     6.300     6.650     7.000.008116224 008653326.009245562
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224   .050498674.059488400
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227        5.600     5.950     6.300     6.650     7.000.090090090.093023256.096153846
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231       17         1.
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233        2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
234        5.600     5.950     6.300     6.650     7.000.007831467.008340110.008899964
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237   .046248121.054083288
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239        2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
240        5.600     5.950     6.300     6.650     7.000.088495575.091324201.094339623
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244       18         1.
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247        5.600     5.950     6.300     6.650     7.000.007561437.008043596.008573388
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253        5.600     5.950     6.300     6.650     7.000.086956522.089686099.092592593
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256   .206185567.222222222
257       19         1.
258          0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
259        2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
260        5.600     5.950     6.300     6.650     7.000.007305136.007762619.008264463
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263   .039211842.045269353
264          0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
265        2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
266        5.600     5.950     6.300     6.650     7.000.085470085.088105727.090909091
267   .093896714.097087379.100502513.104166667.108108108.112359551.116959064.121951220
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269   .198019802.212765957
270       20         1.
271          0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
272        2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
273        5.600     5.950     6.300     6.650     7.000.007061648.007496111.007971939
274   .008494553.009070295.009706617.010412328.011197895.012075836.013061224.014172336
275   .015431503.016866251.018510806.020408163.022612923.025195263.028246593.031887755
276   .036281179.041649313
277          0.0     0.350     0.700     1.050     1.400     1.750     2.100     2.450
278        2.800     3.150     3.500     3.850     4.200     4.550     4.900     5.250
279        5.600     5.950     6.300     6.650     7 000.084033613.086580087.089285714
280   .092165899.095238095.098522167.102040816.105820106.109890110.114285714.119047619
281   .124223602.129870130.136054422.142857143.150375940.158730159.168067227.178571429
282   .190476190.204081633
283        1         1    2    1    0         0.
284        2         2    3    2    0         0.
285        3         3    4    3    0         0.
286        4         4    5    4    0         0.
287        5         5    6    5    0         0.
288        6         6    7    6    0         0.
289        7         7    8    7    0         0.
290        8         8    9    8    0         0.
291        9         9   10    9    0         0.
292       10        10   11   10    0         0.
293       11        11   12   11    0         0.
294       12        12   13   12    0         0.
295       13        13   14   13    0         0.
296       14        14   15   14    0         0.
297       15        15   16   15    0         0.
298       16        16   17   16    0         0.
299       17        17   18   17    0         0.
300       18        18   19   18    0         0.
301       19        19   20   19    0         0.
302       20        20   21   20    0         0.
303   STOP
------ --------------------------------------------------------------------------------
 CARD           1         2         3         4         5         6         7         8
NUMBER 12345678901234567890123456789012345678901234567890123456789012345678901234567890
                              C O L U M N     N U M B E R
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A.18 Small strain-thick layer: Davis (1971)

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                                     C O L U M N   N U M B E R
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
------  --------------------------------------------------------------------------------
   1     1-D CONSOLDN (SMALL STR, THICK LYR, APPR:CONST Cv & e-logp, D.DR) DATA:Davis73(Tv=.2) EO:A4
   2       21    0    1    1    1         0.   10
   3        1    0
   4
   5
   6
   7
   8
   9       10
  10             .125
  11        1    1         0.        0.        0.    0
  12        2    0         0.        0.       .25    1
  13       21    1         0.        0.        5.
  14        1    1
  15               .01       .01       .01       .01       .01       .01
  16               .01       .01       .01       .01       .01       .01
  17               .01       .01       .01       .01       .01       .01
  18               .01
  19        1    2    0    0
  20        1    2
  21              0.        0.       10.        0.
  22        1   20    1                                           4   20   42   42
  23        1         1.
  24       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  25       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  26       0.00800   0.00850   0.00900   0.00950   0.01000 .442477876.442575781.442673749
  27    .442771751.442869786.442967885.443066017.443164182.443262411.443360674.443458980
  28    .443557330.443655723.443754160.443852641.443951165.444049734.444148346.444247001
  29    .444345701.444444444
  30       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  31       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  32       0.00800   0.00850   0.00900   0.00950   0.01000 .442477876.442575781.442673749
  33    .442771751.442869786.442967885.443066017.443164182.443262411.443360674.443458980
  34    .443557330.443655723.443754160.443852641.443951165.444049734.444148346.444247001
  35    .444345701.444444444
  36        2         1.
  37       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  38       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  39       0.00800   0.00850   0.00900   0.00950   0.01000 .362318841.362384490.362450163
  40    .362515860.362581581.362647325.362713094.362778886.362844702.362910543.362976407
  41    .363042294.363108206.363174142.363240102.363306085.363372093.363438125.363504180
  42    .363570260.363636364
  43       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  44       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  45       0.00800   0.00850   0.00900   0.00950   0.01000 .362318841.362384490.362450163
  46    .362515860.362581581.362647325.362713094.362778886.362844702.362910543.362976407
  47    .363042294.363108206.363174142.363240102.363306085.363372093.363438125.363504180
  48    .363570260.363636364
  49        3         1
  50       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  51       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  52       0.00800   0.00850   0.00900   0.00950   0.01000 .306748466.306795521.306842590
  53    .306889673.306936771.306983883.307031010.307078151.307125307.307172477.307219662
  54    .307266861.307314075.307361303.307408546.307455803.307503075.307550361.307597662
  55    .307644978.307692308
  56       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  57       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  58       0.00800   0.00850   0.00900   0.00950   0.01000 .306748466.306795521.306842590
  59    .306889673.306936771.306983883.307031010.307078151.307125307.307172477.307219662
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  61    .307644978.307692308
  62        4         1
  63       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  64       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
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  66    .266063589.266098989.266134398.266169816.266205244.266240682.266276128.266311585
  67    .266347050.266382525.266418010.266453504.266489007.266524520.266560043.266595575
  68    .266631116.266666667
  69       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  70       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  71       0.00800   0.00850   0.00900   0.00950   0.01000 .265957447.265992818.266028199
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  74    .266631116.266666667
  75        5         1.
  76       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  77       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  78       0.00800   0.00850   0.00900   0.00950   0.01000 .234741784.234769339.234796901
  79    .234824469.234852043.234879624.234907212.234934806.234962406.234990013.235017626
  80    .235045246.235072873.235100505.235128145.235155791.235183443.235211102.235238767
  81    .235266439.235294118
  82       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  83       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  84       0.00800   0.00850   0.00900   0.00950   0.01000 .234741784.234769339.234796901
  85    .234824469.234852043.234879624.234907212.234934806.234962406.234990013.235017626
  86    .235045246.235072873.235100505.235128145.235155791.235183443.235211102.235238767
  87    .235266439.235294118
  88        6         1.
  89       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
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  91       0.00800   0.00850   0.00900   0.00950   0.01000 .210084034.210106104.210128178
  92    .210150257.210172341.210194430.210216523.210238621.210260723.210282830.210304942
  93    .210327068.210349180.210371305.210393436.210415571.210437710.210459855.210482004
  94    .210504157.210526316
  95       0.0       0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
  96       0.00400   0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
  97       0.00800   0.00850   0.00900   0.00950   0.01000 .210084034.210106104.210128178
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     8          1.
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     9          1.
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   0.00800     0.00850   0.00900   0.00950   C.01000.128865979.128874283.128882588
.128890894.128899201.128907509.128915818 128924128.128932439.128940752.128949065
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   0 00400     0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
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        .108102265.108108108
            16          1.
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            17          1.
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            0.00400     0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
            0.00800     0.00850   0.00900   0.00950   0.01000.092936803.092941122.092945441
        .092949761.092954081.092958401.092962722.092967043.092971365.092975687.092980009
        .092984332.092988655.092992979.092997303.093001628.093005952.093010278.093014603
        .093018929.093023256
            0.0         0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
            0.00400     0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
            0.00800     0.00850   0.00900   0.00950   0.01000.092936803.092941122.092945441
        .092949761.092954081.092958401.092962722.092967043.092971365.092975687.092980009
        .092984332.092988655.092992979.092997303.093001628.093005952.093010278.093014603
        .093018929.093023256
            19          1.
            0.0         0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
            0.00400     0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
            0.00800     0.00850   0.00900   0.00950   0.01000.088809947.088813890.088817835
        .088821779.088825724.088829669.088833615.088837561.088841507.088845453.088849400
        .088853348.088857295.088861243.088865192.088869140.088873089.088877039.088880988
        .088884938.088888889
            0.0         0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
            0.00400     0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
            0.00800     0.00850   0.00900   0.00950   0.01000.088809947.088813890.088817835
        .088821779.088825724.088829669.088833615.088837561.088841507.088845453.088849400
        .088853348.088857295.088861243.088865192.088869140.088873089.088877039.088880988
        .088884938 088888889
            20          1.
            0.0         0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
            0.00400     0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
            0.00800     0.00850   0.00900   0.00950   0.01000.085034014.085037629.085041245
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        .085073802.085077420.085081040.085084659.085088279.085091899.085095520.085099140
        .085102762.085106383
            0.0         0.00050   0.00100   0.00150   0.00200   0.00250   0.00300   0.00350
            0.00400     0.00450   0.00500   0.00550   0.00600   0.00650   0.00700   0.00750
            0.00800     0.00850   0.00900   0.00950   0.01000.085034014.085037629.085041245
        .085044861.085048478.085052094.085055711.085059329.085062947.085066565.085070183
        .085073802.085077420.085081040.085084659.085088279.085091899.085095520.085099140
        .085102762.085106383
             1           1    2    1    0        0.
             2           2    3    2    0        0.
             3           3    4    3    0        0.
             4           4    5    4    0        0.
             5           5    6    5    0        0.
             6           6    7    6    0        0.
             7           7    8    7    0        0.
             8           8    9    8    0        0.
             9           9   10    9    0        0.
            10          10   11   10    0        0.
            11          11   12   11    0        0.
            12          12   13   12    0        0.
            13          13   14   13    0        0.
            14          14   15   14    0        0.
            15          15   16   15    0        0.
            16          16   17   16    0        0.
            17          17   18   17    0        0.
            18          18   19   18    0        0.
            19          19   20   19    0        0.
            20          20   21   20    0        0.
        STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                  C O L U M N   N U M B E R
```

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                                     C O L U M N   N U M B E R
  CARD             1         2         3         4         5         6         7         8
 NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
 ------   --------------------------------------------------------------------------------
    1      1-D CONSOLDN (Terzaghi's Analysis, D.DR) DATA:Davis71(Tv=.2)
    2        21    1    0    1    1        0.   10
    3         1    0
    4
    5
    6
    7
    8
    9        10
   10           .125
   11         1    1        0.        0.        0.    0
   12         2    0        0.        0.       .25    1
   13        21    1        0.        0.        5.
   14         1    1
   15              .01         .01         .01         .01         .01         .01
   16              .01         .01         .01         .01         .01         .01
   17              .01         .01         .01         .01         .01         .01
   18              .01
   19         1    2    0    0
   20         1    2
   21             0.        0.       10.        0.
   22        1  20   0                                               1   1   0   0
   23         1        1.
   24             1.
   25             1.
   26         1         1    2    1    1         0.
   27        20        20   21    1    0         0.
   28     STOP
 ------   --------------------------------------------------------------------------------
  CARD             1         2         3         4         5         6         7         8
 NUMBER   12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                     C O L U M N   N U M B E R
```

A.19 Small strain-thick layer: Viggiani (1973)

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                                 C O L U M N    N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
   1       1-D CONSOLDN (SMALL STR, THICK LYR, APPR:CONST Cv & e-logp, D.DR) DATA:Viggiani73(Tv=.2) EQ:A4
   2         21    0    1    1    1        0.   10
   3          1    0
   4
   5
   6
   7
   8
   9         10
  10            12.5
  11          1    1        0.        0.        0.    0
  12          2    0        0.        0.       2.5    1
  13         21    1        0.        0.       50.
  14          1    1
  15               10.         10.         10.         10.         10.         10.
  16               10.         10.         10          10.         10.         10.
  17               10.         10.         10.         10.         10.         10.
  18               10.
  19          1    2    0    0
  20          1    2
  21             0.         0.       500.        0.
  22        1  20    1                                              4  20  42  42
  23          1        1.
  24             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  25           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  26           8.000     8.500     9.000     9.500    10.000.074074074.076923077.080000000
  27      .083333333.086956522.090909091.095238095.100000000.105263158.111111111.117647059
  28      .125000000.133333333.142857143.153846154.166666667.181818182.200000000.222222222
  29      .250000000.285714286
  30             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  31           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  32           8.000     8.500     9.000     9.500    10.000.074074074.076923077.080000000
  33      .083333333.086956522.090909091.095238095.100000000.105263158.111111111.117647059
  34      .125000000.133333333.142857143.153846154.166666667.181818182.200000000.222222222
  35      .250000000.285714286
  36          2        1.
  37             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  38           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  39           8.000     8.500     9.000     9.500    10.000.054054054.055555556.057142857
  40      .058823529.060606061.062500000.064516129.066666667.068965517.071428571.074074074
  41      .076923077.080000000.083333333.086956522.090909091.095238095.100000000.105263158
  42      .111111111.117647059
  43             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  44           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  45           8.000     8.500     9.000     9.500    10.000.054054054.055555556.057142857
  46      .058823529.060606061.062500000.064516129.066666667.068965517.071428571.074074074
  47      .076923077.080000000.083333333.086956522.090909091.095238095.100000000.105263158
  48      .111111111.117647059
  49          3        1.
  50             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  51           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  52           8.000     8.500     9.000     9.500    10.000.042553191.043478261.044444444
  53      .045454545.046511628.047619048.048780488.050000000.051282051.052631579.054054054
  54      .055555556.057142857.058823529.060606061.062500000.064516129.066666667.068965517
  55      .071428571.074074074
  56             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  57           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  58           8.000     8.500     9.000     9.500    10.000.042553191.043478261.044444444
  59      .045454545.046511628.047619048.048780488.050000000.051282051.052631579.054054054
  60      .055555556.057142857.058823529.060606061.062500000.064516129.066666667.068965517
  61      .071428571.074074074
  62          4        1
  63             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  64           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  65           8.000     8.500     9.000     9.500    10.000.035087719.035714286.036363636
  66      .037037037.037735849.038461538.039215686.040000000.040816327.041666667.042553191
  67      .043478261.044444444.045454545.046511628.047619048.048780488.050000000.051282051
  68      .052631579.054054054
  69             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  70           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  71           8.000     8.500     9.000     9.500    10.000.035087719.035714286.036363636
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  73      .043478261.044444444.045454545.046511628.047619048.048780488.050000000.051282051
  74      .052631579.054054054
  75          5        1.
  76             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  77           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  78           8.000     8.500     9.000     9.500    10.000.029850746.030303030.030769231
  79      .031250000.031746032.032258065.032786885.033333333.033898305.034482759.035087719
  80      .035714286.036363636.037037037.037735849.038461538.039215686.040000000.040816327
  81      .041666667.042553191
  82             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  83           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  84           8.000     8.500     9.000     9.500    10.000.029850746.030303030.030769231
  85      .031250000.031746032.032258065.032786885.033333333.033898305.034482759.035087719
  86      .035714286.036363636.037037037.037735849.038461538.039215686.040000000.040816327
  87      .041666667.042553191
  88          6        1
  89             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  90           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  91           8.000     8.500     9.000     9.500    10.000.025974026.026315789.026666667
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  93      .030303030.030769231.031250000.031746032.032258065.032786885.033333333.033898305
  94      .034482759.035087719
  95             0.0     0.500     1.000     1.500     2.000     2.500     3.000     3.500
  96           4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
  97           8.000     8.500     9.000     9.500    10.000.025974026.026315789.026666667
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     7          1.
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     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.022988506 023255814.023529412
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     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
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     8          1.
     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.020618557.020833333.021052632
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     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
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     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.018691589.018867925.019047619
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     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
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.022727273.022988506
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     8.000     8.500     9.000     9.500    10.000.017094017.017241379.017391304
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     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
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.018867925.019047619.019230769.019417476.019607843.019801980.020000000.020202020
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     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.015748031.015873016.016000000
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     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
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.018518519.018691589
    12          1.
     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.014598540.014705882.014814815
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.016949153.017094017
     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.014598540.014705882.014814815
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.016949153.017094017
    13          1.
     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.013605442.013698630.013793103
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.014705882.014814815.014925373.015037594.015151515.015267176.015384615.015503876
.015625000.015748031
     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.013605442.013698630.013793103
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.014705882.014814815.014925373.015037594.015151515.015267176.015384615.015503876
.015625000.015748031
    14          1.
     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.012738854.012820513.012903226
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.013698630.013793103.013888889.013986014.014084507.014184397.014285714.014388489
.014492754.014598540
     0.0       0.500     1.000     1.500     2.000     2.500     3.000     3.500
     4.000     4.500     5.000     5.500     6.000     6.500     7.000     7.500
     8.000     8.500     9.000     9.500    10.000.012738854 012820513.012903226
.012987013.013071895.013157895.013245033.013333333.013422819.013513514.013605442
.013698630.013793103.013888889.013986014.014084507.014184397.014285714.014388489
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.014492754.014598540
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      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000 011976048.012048193.012121212
.012195122.012269939.012345679.012422360.012500000.012578616.012658228.012738854
 012820513.012903226.012987013.013071895.013157895.013245033.013333333.013422819
.013513514.013605442
      0.0        0.500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.011976048.012048193 012121212
.012195122.012269939.012345679.012422360.012500000.012578616.012658228.012738854
.012820513.012903226.012987013.013071895.013157895.013245033.013333333 013422819
.013513514.013605442
    16          1.
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      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.011299435.011363636.011428571
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.012048193.012121212.012195122.012269939.012345679.012422360.012500000.012578616
.012658228.012738854
      0.0        0 500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.011299435.011363636.011428571
.011494253.011560694.011627907.011695906.011764706.011834320.011904762.011976048
.012048193.012121212.012195122.012269939.012345679.012422360.012500000.012578616
.012658228.012738854
    17          1.
      0.0        0.500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.010695187.010752688.010810811
.010869565.010928962 010989011.011049724.011111111 011173184.011235955.011299435
.011363636.011428571.011494253.011560694.011627907.011695906.011764706.011834320
.011904762.011976048
      0.0        0.500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.010695187.010752688.010810811
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.011363636.011428571.011494253.011560694.011627907.011695906.011764706.011834320
.011904762.011976048
    18          1
      0.0        0.500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.010152284.010204082.010256410
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.011235955.011299435
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      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.010152284.010204082.010256410
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.010752688.010810811.010869565.010928962.010989011.011049724.011111111.011173184
.011235955.011299435
    19          1.
      0.0        0.500     1 000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.009661836.009708738.009756098
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.010638298.010695187
      0.0        0.500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.009661836.009708738.009756098
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.010204082.010256410.010309278.010362694.010416667.010471204.010526316.010582011
.010638298.010695187
    20          1.
      0.0        0.500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.009216590.009259259.009302326
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.009708738.009756098.009803922.009852217.009900990.009950249.010000000.010050251
.010101010.010152284
      0.0        0.500     1.000     1.500     2.000     2.500     3.000     3.500
      4.000      4.500     5.000     5.500     6.000     6.500     7.000     7.500
      8.000      8.500     9.000     9.500    10.000.009216590.009259259.009302326
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.009708738.009756098.009803922.009852217.009900990.009950249.010000000.010050251
.010101010.010152284
     1          1    2    1    0         0.
     2          2    3    2    0         0.
     3          3    4    3    0         0.
     4          4    5    4    0         0.
     5          5    6    5    0         0.
     6          6    7    6    0         0.
     7          7    8    7    0         0.
     8          8    9    8    0         0.
     9          9   10    9    0         0.
    10         10   11   10    0         0.
    11         11   12   11    0         0.
    12         12   13   12    0         0.
    13         13   14   13    0         0.
    14         14   15   14    0         0.
    15         15   16   15    0         0.
    16         16   17   16    0         0.
    17         17   18   17    0         0.
    18         18   19   18    0         0.
    19         19   20   19    0         0.
    20         20   21   20    0         0.
STOP
--------------------------------------------------------------------------------
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
```

CARD NUMBER

C O L U M N   N U M B E R

```
                              C O L U M N    N U M B E R
 CARD             1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
------  --------------------------------------------------------------------------------
   1     1-D CONSOLDN (Terzaghi's Analysis, D.DR) DATA:Viggiani73(Tv=.2)
   2       21    1    0    1    1        0.   10
   3        1    0
   4
   5
   6
   7
   8
   9       10
  10         31.25
  11        1    1        0.        0.        0.    0
  12        2    0        0.        0.       2.5    1
  13       21    1        0.        0.       50.
  14        1    1
  15             10.         10.         10.         10.         10.         10.
  16             10.         10.         10.         10.         10.         10.
  17             10.         10.         10.         10.         10.         10.
  18             10.
  19        1    2    0    0
  20        1    2
  21            0.        0.      500.        0.
  22       1  20   0                                               1   1   0   0
  23        1        1.
  24            1.
  25            1
  26        1         1    2    1    1        0.
  27       20        20   21    1    0        0.
  28    STOP
------  --------------------------------------------------------------------------------
 CARD             1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                              C O L U M N    N U M B E R
```

A.20 Thick layer: logarithmic material law and constant coefficient of consolidation

```
                                      C O L U M N   N U M B E R
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
......  --------------------------------------------------------------------------------
    1    1-D CONSOLDN (SMALL STR, THICK LYR, APPR CONST Cv & e-logp, D DR, EQ A4
    2     21     0    1    1    1       0.    10
    3       1    0
    4
    5
    6
    7
    8
    9      10
   10   711974814
   11       1    1        0          0         0     0
   12       2    0        0          0          5    1
   13      21    1        0          0        10
   14       1    1
   15            10          10          10          10          10          10
   16            10          10          10          10          10          10
   17            10          10          10          10          10          10
   18            10
   19       1    2    0    0
   20       1    2
   21          0         0       100          0
   22      1  20   1                                               4  20  42  42
   23       1       1
   24          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   25          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   26          8 0       8 5       9 0       9 5      10 0 010014084 010521404 011082868
   27    011707634 012407046 013195336 014090590 015116164 016302748 017691490 019338862
   28    021324531 023764626 026835301 030817261 036186851 043822464 055542145 075818773
   29    119412322 280950595
   30          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   31          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   32          8 0       8 5       9 0       9 5      10 0 010014084 010521404 011082868
   33    011707634 012407048 013195336 014090590 015116164 016302748 017691490 019338862
   34    021324531 023764626 026835301 030817261 036186851 043822464 055542145 075818773
   35    119412322 280950595
   36       2       1
   37          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   38          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   39          8 0       8 5       9 0       9 5      10 0 010520756 011023061 011575735
   40    012186754 012865873 013625147 014479658 015448524 016556345 017835325 019328451
   41    021094419 023215535 025810511 029059626 033243902 038835849 046689472 058524692
   42    078397523 118705562
   43          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   44          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   45          8 0       8 5       9 0       9 5      10 0 010520756 011023061 011575735
   46    012186754 012865873 013625147 014479658 015448524 016556345 017835325 019328451
   47    021094419 023215535 025810511 029059626 033243902 038835849 046689472 058524692
   48    078397523 118705562
   49       3       1
   50          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   51          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   52          8 0       8 5       9 0       9 5      10 0 010555868 011030295 011549384
   53    012119738 012749352 013447965 014227580 015103150 016093553 017222965 018522861
   54    020034993 021815960 023944450 026533179 029749517 033853182 039270125 046750861
   55    057752357 075525048
   56          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   57          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   58          8 0       8 5       9 0       9 5      10 0 010555868 011030295 011549384
   59    012119738 012749352 013447965 014227580 015103150 016093553 017222965 018522861
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   61    057752357 075525048
   62       4       1
   63          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   64          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   65          8 0       8 5       9 0       9 5      10 0 010417696 010858690 011338670
   66    011863045 012438273 013072129 013774056 014555643 015431265 016418980 017541783
   67    018829423 020321076 022069396 024146867 026656102 029747310 033649517 038730070
   68    045617620 055484729
   69          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   70          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   71          8 0       8 5       9 0       9 5      10 0 010417696 010858690 011338670
   72    011863045 012438273 013072129 013774056 014555643 015431265 016418980 017541783
   73    018829423 020321076 022069396 024146867 026656102 029747310 033649517 038730070
   74    045617620 055484729
   75       5       1
   76          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   77          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   78          8 0       8 5       9 0       9 5      10 0 010198672 010605778 011046737
   79    011525954 012048635 012620973 013250397 013945897 014718453 015581623 016552343
   80    017652048 018908277 020357007 022046158 024040993 026432746 029352969 032998567
   81    037678139 043904264
   82          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   83          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   84          8 0       8 5       9 0       9 5      10 0 010198672 010605778 011046737
   85    011525954 012048635 012620973 013250397 013945897 014718453 015581623 016552343
   86    017652048 018908277 020357007 022046158 024040993 026432746 029352969 032998567
   87    037678139 043904264
   88       6       1
   89          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
   90          4 0       4 5       5 0       5 5       6 0       6 5       7 0       7 5
   91          8 0       8 5       9 0       9 5      10 0 009940184 010314906 010718988
   92    011156020 011630204 012146487 012710737 013329964 014012615 014768958 015611609
   93    016556234 017622536 018835643 020228114 021842903 023737873 025992872 028721273
   94    032089633 036353028
   95          0 0       0 5       1 0       1 5       2 0       2 5       3 0       3 5
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```

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.032089633 036353028
     7         1.
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.009663960.010008577.010378681
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     8         1.
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.009382159.009699174.010038362
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      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
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    10         1.
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      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.008561706.008810274.009073707
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    12         1.
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.008305447.008535407.008778464
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244      18        1.
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246          4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
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287       5         5    6    5    0        0.
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290       8         8    9    8    0        0.
291       9         9   10    9    0        0.
292      10        10   11   10    0        0.
293      11        11   12   11    0        0.
294      12        12   13   12    0        0.
295      13        13   14   13    0        0.
296      14        14   15   14    0        0.
297      15        15   16   15    0        0.
298      16        16   17   16    0        0.
299      17        17   18   17    0        0.
300      18        18   19   18    0        0.
301      19        19   20   19    0        0.
302      20        20   21   20    0        0.
303   STOP
------ --------------------------------------------------------------------------------
 CARD           1         2         3         4         5         6         7         8
NUMBER 12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                      C O L U M N    N U M B E R
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                                       C O L U M N   N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
   1       1-D CONSOLDN (FINITE STR, THICK LYR, APPR:CONST Cv & e-logp, D DR)  EQ:A8
   2         21    0    1    1    1        0.   10
   3          1    0
   4
   5
   6
   7
   8
   9         10
  10      .711974814
  11          1    1         0         0.        0    0
  12          2    0         0         0.       .5    1
  13         21    1         0.        0       10.
  14          1    1
  15               10.         10          10.         10.         10.         10.
  16               10          10          10.         10.         10.         10.
  17               10          10.         10.         10          10.         10.
  18               10
  19          1    2    0    0
  20          1    2
  21              0.         0        50.        0.
  22         1  20   1                                     4  20  42  42
  23          1        1
  24             0 0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
  25             4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
  26             8.0       8.5       9.0       9.5      10.0.023429339.024234334.025114347
  27      .026081020.027148607.028334762 029661636.031157432.032858664.034813518.037087013
  28      .039769207.042988782.046936706.051909988.058399038 067280215.080301304.101569944
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  31             4.0       4.5       5.0       5.5       6.0       6 5       7.0       7.5
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  36          2        1.
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  38             4.0       4.5       5.0       5 5       6.0       6.5       7.0       7.5
  39             8.0       8 5       9.0       9.5      10.0.020280151.020934269.021645637
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  43             0.0       0.5       1 0       1 5       2.0       2.5       3.0       3.5
  44             4.0       4.5       5 0       5.5       6.0       6.5       7.0       7.5
  45             8.0       8.5       9.0       9.5      10.0 010520756.011023061.011575735
  46      .012186754.012865873.013625147 014479658.015448524.016556345.017835325.019328451
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  51             4.0       4.5       5.0       5.5       6.0       6.5       7 0       7.5
  52             8.0       8.5       9 0       9.5      10.0.018346067.018900821.019501130
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  57             4.0       4 5       5.0       5.5       6.0       6.5       7.0       7.5
  58             8.0       8.5       9.0       9.5      10.0.010555868.011030299.011549384
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     4           4    5    4    0         0.
     5           5    6    5    0         0.
     6           6    7    6    0         0.
     7           7    8    7    0         0.
     8           8    9    8    0         0.
     9           9   10    9    0         0.
    10          10   11   10    0         0.
    11          11   12   11    0         0.
    12          12   13   12    0         0.
    13          13   14   13    0         0.
    14          14   15   14    0         0.
    15          15   16   15    0         0.
    16          16   17   16    0         0.
    17          17   18   17    0         0.
    18          18   19   18    0         0.
    19          19   20   19    0         0.
    20          20   21   20    0         0.
STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                     C O L U M N   N U M B E R
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                                      C O L U M N    N U M B E R
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
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 1-D CONSOLDN (FINITE STR, THICK LYR, APPR:CONST Cv & e-logp, D.DR)  EQ:A9
   21    0    1    1    1        0.   10
    1    0





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         10.       10.       10.       10.       10.       10.
         10.       10.       10.       10.       10.       10.
         10.
    1    2    0    0
    1    2
        0.        0.      100.        0.
   1  20    1                                         4  20  42  42
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        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
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.011888728 012309956.012762130.013248789.013774035.014342648.014960228.015633386
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.026273207.028422529
    9          1.
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.010094385.010295202.010506997
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.013120972.013525939.013964840.014442384.014964221.015537192.016169663.016871985
.017657131.018541594
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.010270911.010583790.010916329
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.023432401.025127068
   10          1.
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        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.009793193.009978192.010172815
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.012532847.012891418.013277873.013695793.014149416.014643800.015185033.015780514
.016439334.017172796
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.009806161.010090972.010392823
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.014221481 014828450.015489539.016212325.017005866.017881089.018851287.019932809
.021145980.022516396
   11          1.
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.009514883.009685946.009865498
.010054224.010252887.010462340.010683537.010917554.011165605.011429064.011709500
.012008706.012328744.012671999.013041242.013439721.013871259.014340399.014852579
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        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.009381649.009642008.009917230
.010208626.010517664.010845997.011195490.011568256.011966701.012393572.012852024
.013345696.013878809.014456286.015083905.015768493.016518177.017342704.018253870
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   12          1.
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.009256827.009415542.009581787
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        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
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        8.0         8.5         9.0         9.5        10.0.008992367.009231292.009483260
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        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.009016789.009164509.009318940
.009480577 009649967.009827713.010014486.010211032.010418183.010636873.010868149
.011113196.011373354.011650147.011945320.012260875.012599125.012962756.013354908
.013779278.014240244
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.008634103.008854136.009085678
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.011882235.012302996.012754649.013240727.013765322.014333200.014949949.015622162
.016357671.017165860
   14          1.
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.008792860.008930740.009074632
.009224958.009382187.009546832.009719462.009900706.010091263.010291912.010503524
.010727076.010963667.011214540.011481105.011764969.012067974.012392238.012740215
.013114759.013519218
        0.0         0.5         1.0         1.5         2.0         2.5         3.0         3.5
        4.0         4.5         5.0         5.5         6.0         6.5         7.0         7.5
        8.0         8.5         9.0         9.5        10.0.008303292.008506590.008720092
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.015209644.015905957
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      4 0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.008583394.008712433.008846878
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      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9 0       9.5      10.0.007996896.008185296.008382788
.008590045.008807811.009036905.009278234.009532807.009801744.010086295.010387862
.010708017 011048535.011411421.011798954 012213734.012658738.013137396.013653676
.014212193.014818352
    16         1.
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.008386970.008508031.008633973
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      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.007712308.007887390.008070607
.008262538.008463821 008675155.008897313.009131148.009377606.009637737.009912712
.010203839.010512583.010840594 011189733.011562110.011960124.012386517.012844438
.013337516.013869962
    17         1.
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.008202348.008316183.008434443
.008557404.008685370.008818670.008957664.009102747.009254351.009412951.009579071
.009753290.009936251.010128667.010331334.010545141.010771086.011010296.011264043
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      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.007447279.007610408.007780843
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.009745003.010026222.010324155.010640335.010976494.011334587.011716832.012125758
.012564259 013035666
    18         1.
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.008028446.008135714.008247006
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.011109169.011369074
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.007199859.007352218.007511165
.007677136.007850608.008032100.008222182.008421479.008630678.008850535.009081886
.009325657.009582874.009854684.010142362.010447342.010771231.011115846.011483240
.011875751.012296044
    19         1
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.007864312.007965593.008070544
.008179381.008292336.008409660.008531627.008658534.008790705.008928493.009072285
.009222505.009379620.009544142.009716640.009897741.010088143.010288625.010500054
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      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.006968352.007110973.007259555
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.008940912.009177075.009426052.009688916.009966861.010261224.010573504.010905387
.011258781.011635844
    20         1.
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.007709106.007804911.007904075
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.010371159.010587197
      0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
      4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
      8.0       8.5       9.0       9.5      10.0.006751268.006885056.007024255
.007169197.007320248.007477800.007642284.007814166.007993958.008182219.008379560
.008586656.008804247.009033153.009274280.009528633.009797330.010081622.010382905
.010702750.011042928
     1         1    2    1    0         0.
     2         2    3    2    0         0.
     3         3    4    3    0         0.
     4         4    5    4    0         0.
     5         5    6    5    0         0.
     6         6    7    6    0         0.
     7         7    8    7    0         0.
     8         8    9    8    0         0.
     9         9   10    9    0         0.
    10        10   11   10    0         0.
    11        11   12   11    0         0.
    12        12   13   12    0         0.
    13        13   14   13    0         0.
    14        14   15   14    0         0.
    15        15   16   15    0         0.
    16        16   17   16    0         0.
    17        17   18   17    0         0.
    18        18   19   18    0         0.
    19        19   20   19    0         0.
    20        20   21   20    0         0.
STOP
------  --------------------------------------------------------------------------------
CARD             1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                    C O L U M N     N U M B E R
```

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                                       C O L U M N   N U M B E R
 CARD                1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
------     --------------------------------------------------------------------------------
    1       1-D CONSOLDN (Terzaghi's Analysis, D.DR)
    2         21    1    0    1    1        0.   10
    3          1    0
    4
    5
    6
    7
    8
    9         10
   10      .711974814
   11          1    1        0.        0.        0.    0
   12          2    0        0.        0.        .5    1
   13         21    1        0.        0.       10.
   14          1    1
   15               10.         10.         10.         10.         10.         10.
   16               10.         10.         10.         10.         10.         10.
   17               10.         10.         10.         10.         10.         10.
   18               10.
   19          1    2    0    0
   20          1    2
   21              0.        0.      100.        0.
   22         1  20   0                                               1   1   0   0
   23          1        1.
   24              1.
   25              1.
   26          1         1    2    1    1         0.
   27         20        20   21    1    0         0.
   28      STOP
------     --------------------------------------------------------------------------------
 CARD                1         2         3         4         5         6         7         8
NUMBER     12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                       C O L U M N   N U M B E R
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A.21 Thick layer: Gibson et al (1981)

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                                    C O L U M N   N U M B E R
  CARD             1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLDN (SMALL STR, THICK LYR, APPR CONST Cv, D.DR) DATA:Gibson-eta181 EO A4
     2       21    0    1    1    1         0.   20
     3        1    0
     4
     5
     6
     7
     8
     9       20
    10         150.5
    11        1    1        0.        0.        0.    0
    12        2    0        0.        0.        .5    1
    13       21    1        0.        0        10.
    14        1    1
    15             10          10          10          10.         10.         10
    16             10          10          10.         10          10.         10
    17             10          10          10.         10.         10.         10
    18             10
    19        1    2    0    0
    20        1    2
    21           0.         0      5000         0
    22       1  20   1                                               4  20  42  42
    23        1        1
    24           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    25           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    26           8.0       8.5       9.0       9.5      10.0.111290E-4.131386E-4.155111E-4
    27    .183120E-4.216187E-4.255224E-4.301311E-4.355720E-4.419953E-4.495785E-4.585311E-4
    28    .691002E-4.815779E-4.953087E-4.113699E-3.134230E-3.158469E-3.187084E-3.220866E-3
    29    .260749E-3.307833E-3
    30           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    31           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    32           8.0       8.5       9.0       9.5      10.0.005724816.006758564.007978979
    33    .009418768.011120724.013128828.015499541.018298342.021602530.025503366.030108588
    34    .035545389.041963930.049541487.058487347.069048589.081516906.096236667.113614420
    35    .134130129.158350422
    36        2        1.
    37           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    38           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    39           8.0       8.5       9.0       9.5      10.0.107712E-4.127162E-4.150124E-4
    40    .177232E-4.209236E-4.247018E-4.291623E-4.344282E-4.406450E-4.479844E-4.566491E-4
    41    .668784E-4.789549E-4.932120E-4.110044E-3.129914E-3.153374E-3.181069E-3.213765E-3
    42    .252365E-3.297935E-3
    43           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    44           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    45           8.0       8.5       9.0       9.5      10.0.005540744.006541253.007722427
    46    .009116890.010763155.012706691.015001178.017709987.020907834.024683345.029140493
    47    .034402482.040614645.047948558.056606778.066828439.078895858.093142327.109961326
    48    .129817384.153258912
    49        3        1
    50           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    51           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    52           8.0       8.5       9.0       9.5      10.0.104047E-4.122835E-4.145016E-4
    53    .171202E-4.202117E-4.238614E-4.281701E-4.332568E-4.392621E-4.463518E-4.547217E-4
    54    .646030E-4.762685E-4.900406E-4.106299E-3.125494E-3.148155E-3.174908E-3.206492E-3
    55    .243779E-3.287798E-3
    56           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    57           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    58           8.0       8.5       9.0       9.5      10.0.005352228.006318696.007459682
    59    .008806700.010396954.012274364.014490784.017107429.020196571.023843529.028149028
    60    .033231986.039232789.0463'7175.054680811.064554694.076211536.089973285.106220045
    61    .125400528.148044490
    62        4        1
    63           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    64           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    65           8.0       8.5       9.0       9.5      10.0.100302E-4.118414E-4.139796E-4
    66    .165039E-4.194841E-4.230024E-4.271560E-4.320597E-4.378488E-4.446833E-4.527519E-4
    67    .622774E-4.735231E-4.867993E-4.102473E-3.120977E-3.142822E-3.168612E-3.199059E-3
    68    .235003E-3.277438E-3
    69           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    70           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
    71           8.0       8.5       9.0       9.5      10.0.005159560.006091238.007191152
    72    .008489680.010022688.011832516.013969150.016491603.019469543.022985219.027135731
    73    .032035714.037820503.044649868.052712433.062230881.073468104.086734468.102396379
    74    .120886411.142716245
    75        5        1
    76           0.0       0.5       1.0       1.5       2.0       2.5       3.0       3.5
    77           4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
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    94    .216975E-3.256155E-3
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    11        11   12   11    0         0.
    12        12   13   12    0         0.
    13        13   14   13    0         0.
    14        14   15   14    0         0.
    15        15   16   15    0         0.
    16        16   17   16    0         0.
    17        17   18   17    0         0.
    18        18   19   18    0         0.
    19        19   20   19    0         0.
    20        20   21   20    0         0.
STOP
------        --------------------------------------------------------------------------------
 CARD                  1         2         3         4         5         6         7         8
NUMBER        12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                        C O L U M N   N U M B E R
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                                    C O L U M N     N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
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           1-D CONSOLDN (FINITE STR, THICK LYR, APPR:CONST Cv, D.DR) DATA:Gibson-eta181 EQ:A8
             21    0    1    1    1       0.   20
              1    0





             20
               150.9
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              2    0        0.        0.        .5     1
             21    1        0.        0.       10.
              1    1
                   10.         10.         10.         10.         10.         10.
                   10.         10.         10.         10.         10.         10.
                   10.         10.         10.         10.         10.         10.
                   10.
              1    2    0    0
              1    2
                  0.        0.     5000.        0.
             1  20   1                                               4  20  42  42
              1        1.
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       4.0       4.5       5.0       5.5       6.0       6.5       7.0       7.5
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.047698859.056311990
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    2         2    3    2    0         0.
    3         3    4    3    0         0.
    4         4    5    4    0         0.
    5         5    6    5    0         0.
    6         6    7    6    0         0.
    7         7    8    7    0         0.
    8         8    9    8    0         0.
    9         9   10    9    0         0.
   10        10   11   10    0         0.
   11        11   12   11    0         0.
   12        12   13   12    0         0.
   13        13   14   13    0         0.
   14        14   15   14    0         0.
   15        15   16   15    0         0.
   16        16   17   16    0         0.
   17        17   18   17    0         0.
   18        18   19   18    0         0.
   19        19   20   19    0         0.
   20        20   21   20    0         0.
STOP
------  --------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                              C O L U M N     N U M B E R
```

```
                                        C O L U M N   N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
   1       1-D CONSOLDN (FINITE STR, THICK LYR, APPR:CONST Cv, D.DR) DATA:Gibson-etal81 EO:A9
   2         21    0    1    1    1        0.   20
   3          1    0
   4
   5
   6
   7
   8
   9         20
  10           150.9
  11          1    1        0.        0.        0.    0
  12          2    0        0.        0.     .1364    1
  13         21    1        0.        0.     2.728
  14          1    1
  15                 10.         10.         10.         10.         10.         10.
  16                 10.         10.         10.         10.         10.         10.
  17                 10.         10.         10.         10.         10.         10.
  18                 10
  19          1    2    0    0
  20          1    2
  21                0.        0.     5000.        0.
  22          1  20   1                                               4  20  42  42
  23          1        1.
  24              0.0      0.50      1.00      1.50      2.00      2.50      3.00      3.50
  25             4.00      4.50      5.00      5.50      6.00      6.50      7.00      7.50
  26             8.00      8.50      9.00      9.50     10.00.793902E-5.926644E-5.107945E-4
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  28      .363344E-4.403980E-4.445319E-4.486263E-4.525511E-4.561620E-4.593090E-4.618481E-4
  29      .636542E-4.646333E-4
  30              0.0      0.50      1.00      1.50      2.00      2.50      3.00      3.50
  31             4.00      4.50      5.00      5.50      6.00      6.50      7.00      7.50
  32             8.00      8.50      9.00      9.50     10.00.027001384.031877108.037633256
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  35      .632631511.746867746
  36          2        1.
  37              0.0      C.50      1.00      1.50      2.00      2.50      3.00      3.50
  38             4.00      4.50      5.00      5.50      6.00      6 50      7.00      7.50
  39             8.00      8.50      9.00      9.50     10.00.737277E-5.861270E-5.100427E-4
  40      .116852E-4.135624E-4.156959E-4 181043E-4.208020E-4.237960E-4.270834E-4.306479E-4
  41      .344560E-4.384545E-4.425674E-4.466956E-4.507182E-4.544967E-4.578825E-4.607272E-4
  42      .628951E-4.642761E-4
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  44             4.00      4.50      5.00      5.50      6.00      6.50      7.00      7.50
  45             8.00      8.50      9.00      9.50     10.00.024955458.029461743.034781741
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  51             4.00      4.50      5.00      5.50      6.00      6.50      7.00      7.50
  52             8.00      8.50      9.00      9.50     10.00.684448E-5.800178E-5.933883E-5
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  57             4.00      4.50      5.00      5.50      6.00      6.50      7.00      7.50
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  64             4.00      4.50      5.00      5.50      6.00      6.50      7.00      7.50
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      4.00      4.50       5.00       5.50       6.00       6.50       7.00       7.50
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   17         1.
      0.0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.235587E-5.277209E-5.325991E-5
.383092E-5.449827E-5.527681E-5.618315E-5.723563E-5.845420E-5.986023E-5.114760E-4
.133239E-4.154255E-4.178001E-4.204624E-4.234208E-4.266736E-4.302062E-4.339875E-4
.379666E-4.420705E-4
      0.0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.007653471 009035482.010667047
.012593229.014867227.017551849.020721241.024462939.028880288.034095291.040251984
.047520409.056101317.066231706.078191371.092310629.108979445.128658202.151890412
.179317735.211697695
   18         1.
      0.0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.218039E-5.256625E-5.301873E-5
.354871E-5.416858E-5.489239E-5.573588E-5.671660E-5.785374E-5.916806E-5.106815E-4
.124164E-4.143950E-4.166378E-4.191621E-4.219795E-4.250935E-4.284960E-4.321643E-4
.360572E-4.401125E-4
      0 0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.007073559.008350853.009858793
.011639026.013740721.016221925.019151169.022609355.026691996.031511852.037202045
.043919734.051850456.061213254.072266721.085316147.100721949.118909624.140381503
.165730626.195657120
   19         1.
      0.0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.201778E-5.237540E-5.279499E-5
.328673E-5.386229E-5.453490E-5.531951E-5.623279E-5.729318E-5.852074E-5.993685E-5
.115638E-4.134241E-4.155391E-4.179279E-4.206052E-4.235786E-4.268460E-4.303921E-4
 341848E-4.381722E-4
      0.0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.006537587.007718100.009111781
.010757124.012699571.014992772.017700063.020896218.024669513.029124163.034383204
.040591886.047921688.056575056.066790990.078851646.093090132.109899706.129744637
.153173028.180831957
   20         1.
      0.0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.186711E-5.219849E-5.258748E-5
.304361E-5.357784E-5.420262E-5.493210E-5.578211E-5.677027E-5 791588E-5.923975E-5
.107638E-4.125106E-4.145021E-4.167588E-4.192977E-4.221301E-4.252590E-4.286757E-4
.323565E-4.362594E-4
      0.0         0.50        1.00        1.50        2.00        2.50        3.00        3.50
      4.00        4.50        5.00        5.50        6.00        6.50        7.00        7.50
      8.00        8.50        9.00        9.50       10.00.006042227.007133291.008421371
.009942044.011737310.013856752.016358909.019312888.022800276.026917392.031777949
.037516192.044290608.052288300.061730160.072876967.086036587.101572480.119913738
.141566934.167130114
    1          1    2    1    0         0.
    2          2    3    2    0         0.
    3          3    4    3    0         0.
    4          4    5    4    0         0.
    5          5    6    5    0         0.
    6          6    7    6    0         0.
    7          7    8    7    0         0.
    8          8    9    8    0         0.
    9          9   10    9    0         0.
   10         10   11   10    0         0.
   11         11   12   11    0         0.
   12         12   13   12    0         0.
   13         13   14   13    0         0.
   14         14   15   14    0         0.
   15         15   16   15    0         0.
   16         16   17   16    0         0.
   17         17   18   17    0         0.
   18         18   19   18    0         0.
   19         19   20   19    0         0
   20         20   21   20    0         0.
STOP
------  ------------------------------------------------------------------------------
 CARD            1         2         3         4         5         6         7         8
NUMBER  12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                  C O L U M N    N U M B E R
```

```
                                        C O L U M N    N U M B E R
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
------    --------------------------------------------------------------------------------
     1     1-D CONSOLDN (Terzaghi's Analysis, D.DR) DATA:Gibson-eta181
     2       21    1    0    1    1        0.   20
     3        1    0
     4
     5
     6
     7
     8
     9       20
    10         150.9
    11        1    1        0.        0.        0.    0
    12        2    0        0.        0.        .5    1
    13       21    1        0.        0.       10.
    14        1    1
    15             10.         10.         10.         10.         10.         10.
    16             10.         10.         10.         10.         10.         10.
    17             10.         10.         10.         10.         10.         10.
    18             10.
    19        1    2    0    0
    20        1    2
    21            0.        0.     5000.        0.
    22       1  20   0                                               1   1   0   0
    23        1        1
    24       .001944
    25            1.
    26        1         1    2    1    1        0.
    27       20        20   21    1    0        0.
    28    STOP
------    --------------------------------------------------------------------------------
 CARD              1         2         3         4         5         6         7         8
NUMBER    12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                        C O L U M N    N U M B E R
```

APPENDIX B

Computer Programs

LIST OF PROGRAMS

Program Page

Note: Most of these computer programs are written for the illustrated examples in this text. Modifications of these programs are necessary for their general use.

B.1 Terzaghi's classical analysis

```
C     ***************************************************************
C     *                                                             *
C     *                   *** TERZAGHI25 ***                        *
C     *      This program is to compute the excess pore pressure    *
C     *  at various depth and time according to Terzaghi's          *
C     *  classical theory of consolidation                          *
C     *                                                             *
C     ***************************************************************
      DOUBLE PRECISION ZH(25),TV(15),UE(15,25),AM,AMT,AMZ
      DOUBLE PRECISION DSIN,DEXP,DFLOAT
      TV(1)=0.05D0
      DO 8 IJ=2,4
    8 TV(IJ)=TV(IJ-1)+0.05D0
      DO 10 II=5,11
   10 TV(II)=TV(II-1)+0.1D0
      ZH(1)=0.05D0
      DO 15 JJ=2,20
   15 ZH(JJ)=ZH(JJ-1)+0.05D0
      DO 20 I=1,11
      DO 20 J=1,20
      UE(I,J)=0.D0
      DO 20 K=1,50
      KM=K-1
      AM=(2.D0*DFLOAT(KM)+1.D0)*3.141592654D0/2.D0
      AMZ=AM*ZH(J)
      AMT=-1.D0*TV(I)*AM**2
      UE(I,J)=UE(I,J)+DSIN(AMZ)*DEXP(AMT)*2.D0/AM
   20 CONTINUE
      WRITE(6,60)
      WRITE(6,61)(TV(I),I=1,11)
      DO 25 L=1,20
   25 WRITE(6,62)ZH(L),(UE(I,L),I=1,11)
   60 FORMAT('0'/' Depth',44X,'Time Factor   Tv')
   61 FORMAT(' Ratio',11F9.2//)
   62 FORMAT(F6.2,2X,11F9.6)
      STOP
      END
```

B.2 Gray's two-layered analysis

```
C     ***************************************************************
C     *                                                             *
C     *                   *** Gray45 ***                            *
C     *      This program is to find the analytical solution of     *
C     *  the excess pore water pressure for two-layered soils       *
C     *  according to Gray H. (1945) for certain values of sigma,   *
C     *  mu, lambda as given below                                  *
C     *                                                             *
C     ***************************************************************
C
      DOUBLE PRECISION AN(10),TV(5),ZH(25),UE(5,25),CN,PARC,PARMA,TNPP
      DOUBLE PRECISION PARAZ,AMU,SIGMA,ALAMDA
      AN(1)=0.0714326347
      AN(2)=0.215
      AN(3)=0.3604
      AN(4)=0.5078
      AN(5)=0.6571
      AN(6)=0.8076
      AN(7)=0.9593
      AN(8)=1.1117
      SIGMA=2.0
      ALAMDA=4.0
      AMU=5.0
      TV(1)=20.0
      TV(2)=100.0
      TV(3)=200.0
      ZH(1)=5.0
      DO 10 II=2,21
   10 ZH(II)=ZH(II-1)-0.25
      DO 20 I=1,3
      DO 20 J=1,21
      UE(I,J)=0.0
      DO 20 K=1,8
      PARC=AMU*ALAMDA*AN(K)
      CN=2.*DCOS(AN(K))/(SIGMA*AN(K)*DSIN(PARC)**2+PARC*DCOS(AN(K))**2)
      TNPP=-1.*TV(I)*AN(K)*AN(K)
      IF(J.GE.18) GO TO 16
      PARMA=AMU*AN(K)*(1.+ALAMDA-ZH(J))
      UE(I,J)=UE(I,J)+CN*DEXP(TNPP)*DCOS(AN(K))*DSIN(PARMA)
      GO TO 20
   16 PARAZ=AN(K)*ZH(J)
      UE(I,J)=UE(I,J)+CN*DEXP(TNPP)*DCOS(PARAZ)*DSIN(PARC)
   20 CONTINUE
      WRITE(6,63)
      WRITE(6,60)
      WRITE(6,61)(TV(I),I=1,3)
      DO 25 L=1,21
   25 WRITE(6,62)ZH(L),(UE(I,L),I=1,3)
      STOP
   60 FORMAT(' Depth',8X,'Time Factor   Tv')
   61 FORMAT(' Ratio',3F9.0//)
   62 FORMAT(F6.2,2X,3F9.6)
   63 FORMAT('0'//4X,'Analytical Solution by Grey'//)
      END
```

B.3 Martins' closed-form solution

```
C       *****************************************************************
C       *                                                               *
C       *                      *** MARTINS65 ***                        *
C       *                                                               *
C       *   # One dimensional consolidation with linear spatial         *
C       *     variation of permeability #                               *
C       *                                                               *
C       *      This program is to calculate the excess pore pressure    *
C       *   at various depth at time t according to Martins'            *
C       *   analytical solution in 1965. The soil layer is assumed      *
C       *   to drain freely at both top and bottom.                     *
C       *                                                               *
C       *   Input variables:                                            *
C       *   T = Time required, sec                                      *
C       *   KO = The coefficient of permeability, cm/sec                *
C       *   MV = The coefficient of volume compressibility, cm**2/g     *
C       *   BETA = A dimensionless contant relates to the variation     *
C       *          of permeability by the eqn: K = KO(1+BETA*Z)         *
C       *   GAMMA = Unit weight of soil, g/cm**3                        *
C       *   GAMMAW = Unit weight of water, g/cm**3                      *
C       *   H2 = Total thickness of soil, cm                            *
C       *   UO = Initial uniform pore pressure, g/cm**2                 *
C       *   NOEL = Number of equal segments of the soil profile         *
C       *          specified for the outputs                            *
C       *   AN(n) = Roots of the eqn. JO(A).YO(kA)-JO(kA).YO(A)=0       *
C       *           where k is the variable LAMBDA in the program       *
C       *   NORT = Total number of the above roots used                 *
C       *                                                               *
C       *   Use of the program                                          *
C       *   1  First to compile the program by:                         *
C       *   RUN *FORTGTEST SCARDS=MARTINS65 SPRINT=-1 PAR=ID,SOURCE     *
C       *   2  Repeat the following for subsequent executions           *
C       *   DEBUG -LOAD#+*IMSLDPLIB 5=datafile 6=output                 *
C       *                                                               *
C       *   Remarks:                                                    *
C       *   The routines MMBSJO and MMBSYN in the IMSL Library will     *
C       *   be used. Their descriptions are shown at the back of this   *
C       *   program                                                     *
C       *                                                               *
C       *****************************************************************
C
        IMPLICIT REAL*8(A-H,O-Z)
        REAL*8 KO,MV,LAMBDA,DSORT,DEXP,DFLOAT,MMBSJO
        DIMENSION AN(10),ALA(10),BJOLA(10),UT(10),Z(100),ZH(100),UE(100)
C
C       *****************************************************************
C       *                                                               *
C       *   Read all input date                                         *
C       *                                                               *
C       *****************************************************************
C
        READ(5,50)T,KO,MV,BETA,H2
        READ(5,51)NOEL,NORT,UO,GAMMA,GAMMAW
        READ(5,52)(AN(I),I=1,NORT)
C
C       *****************************************************************
C       *                                                               *
C       *   Calculation of the average consolidation at the given       *
C       *   time T                                                      *
C       *                                                               *
C       *****************************************************************
C
        LAMBDA=DSORT(1.DO+BETA)
        CHI=BETA*BETA*KO/(4.DO*H2*H2*GAMMAW*MV)
        ACT=0.DO
C
        DO 15 I=1,NORT
        ALA(I)=LAMBDA*AN(I)
        BJOA=MMBSJO(AN(I),IEJ1)
        BJOLA(I)=MMBSJO(ALA(I),IEJ2)
        EJ=DEXP(-1.DO*CHI*AN(I)*AN(I)*T)/(BJOA+BJOLA(I))
        UT(I)=BJOA*EJ
        ACT=ACT+(BJOA-BJOLA(I))*EJ/(AN(I)*AN(I))
     15 CONTINUE
C
        AVCON=4.DO*ACT/BETA
C
C       *****************************************************************
C       *                                                               *
C       *   Compute the excess pore pressure at various depth           *
C       *                                                               *
C       *****************************************************************
C
        PI=3.14159265358979323846264338327950288419716939937511DO
        NONOD=NOEL+1
        DIV=H2/DFLOAT(NOEL)
        Z(1)=0.DO
C
        DO 20 J=1,NONOD
        Z(J+1)=Z(J)+DIV
        ZH(J)=Z(J)/H2
        R=DSORT(1.DO+BETA*ZH(J))
        UET=0.DO
C
        DO 18 L=1,NORT
        RA=R*AN(L)
        BJORA=MMBSJO(RA,IEJ3)
        CALL MMBSYN(RA,0.DO,1,YORA,IEY1)
        CALL MMBSYN(ALA(L),0.DO,1,YOLA,IEY2)
        UET=UET+UT(L)*(BJORA*YOLA-BJOLA(L)*YORA)
     18 CONTINUE
```

```
C
      UE(J)=UO*PI*UET
   20 CONTINUE
C
C     ***************************************************************
C     *                                                             *
C     *  Output quantities                                          *
C     *                                                             *
C     ***************************************************************
C
      WRITE(6,60)
      WRITE(6,61)AVCON
      WRITE(6,62)KO,BETA,MV,H2,GAMMA,GAMMAW,UO,LAMBDA,CHI,NORT,NOEL
      WRITE(6,63)T,(Z(I),ZH(I),I,UE(I),I=1,NONOD)
      WRITE(6,64)IEJ1,IEJ2,IEJ3,IEY1,IEY2
C
      STOP
C
C     ***************************************************************
C     *                                                             *
C     *  Format statments                                           *
C     *                                                             *
C     ***************************************************************
C
   50 FORMAT(5G20.0)
   51 FORMAT(2I5,3G20.0)
   52 FORMAT(3F20.0)
C
   60 FORMAT('1'////6X'The One Dimensional Consolidation with ',
     1'Linear Spatial'/18X'Variation of Permeability'
     1//13X'Analytical Solution by Martins (1965)'///)
   61 FORMAT(4X'Average Consolidation =',F12.8///)
   62 FORMAT(4X'KO      =',E15.6/4X'Beta    =',F15.5/
     14X'Mv      =',E15.6/4X'2H      =',F15.5/
     14X'GAMMA   =',F15.5/4X'GAMMAW =',F15.5/
     14X'UO      =',F15.5/4X'Lambda =',F15.5/
     14X'Chi     =',E15.7/4X'No of roots used =',I5/
     14X'No of elements    =',I5///)
   63 FORMAT(13X'Excess pore pressure vs depth:'//
     113X'Depth',6X'Depth',4X'NODE',9X'Time t'/24X'Ratio',10XG20.9
     1//(9XF11.5,F10.4,3XI3,4XE15.8))
   64 FORMAT(////5X'Error message from the *IMSLDPLIB for the final'
     1,' iteration:'//5X'IEJ1  IEJ2  IEJ3  IEY1  IEY2'/3X5I6)
C
C     ***************************************************************
C     *                                                             *
C     *                       # IMSL Library #                      *
C     *                                                             *
C     *  The following is a brief description of the Fortran        *
C     *  routines used in this program.  This information is        *
C     *  available in the IMSL Library reference manual, edition    *
C     *  8, 1980. The routines with single precision are stored     *
C     *  in the public file *IMSLLIB, those with double precision   *
C     *  are stored in *IMSLDPLIB.                                  *
C     *                                                             *
C     *                                                             *
C     *  Routine name:  MMBSJO                                      *
C     *                                                             *
C     *  Usage:  FUNCTION MMBSJO(ARG,IER)                           *
C     *                                                             *
C     *  Description of arguments:                                  *
C     *  ARG - Input argument                                       *
C     *  IER - Error parameter, terminal error                      *
C     *                                                             *
C     *                                                             *
C     *  Routine name: MMBSYN                                       *
C     *                                                             *
C     *  Usage: CALL MMBSYN(ARG,ORDER,N,YN,IER)                     *
C     *                                                             *
C     *  Description of arguments:                                  *
C     *  ARG   - Input argument                                     *
C     *  ORDER - Desired order, which must be greater than or       *
C     *          equal to zero and less than one                    *
C     *  N     - Number of results required, with which order       *
C     *          start from 'ORDER' to 'ORDER+1' to 'ORDER+2', etc  *
C     *  YN    - Output vector of above results                     *
C     *  IER   - Error parameter where                              *
C     *          '129': ORDER is out of range or ARG is less than   *
C     *                 the minimum allowable value                 *
C     *          '130': N is less than or equal to zero             *
C     *          '131': YN overflow                                 *
C     *          '132': ARG is greater than the maximum allowable   *
C     *                 value                                       *
C     *                                                             *
C     ***************************************************************
C
      END
```

B.4 Edelmann's closed-form solution

```
C       ******************************************************************
C       *                                                                *
C       *                      *** EDELMANN53 ***                        *
C       *                                                                *
C       *  # One dimensional consolidation with the modulus of           *
C       *    elasticity proportional to the depth #                      *
C       *                                                                *
C       *      This program is to compute the excess pore pressure       *
C       *  at various depth at time t according to Edelmann's            *
C       *  analytical solution in 1953. The soil layer is assumed        *
C       *  to drain at the top only.                                     *
C       *                                                                *
C       *  Input variables:                                              *
C       *  T = Time required, sec                                        *
C       *  SIGMAO = A small initial effective stress, g/cm**2            *
C       *  C = A dimensionless constant, relates to compressibility      *
C       *       by the eqn. Mv=1/(C*Gamma*Z+SigmaO)                      *
C       *       where Z is the distance in cm from the surface           *
C       *  GAMMA = Unit weight of soil, g/cm**3                          *
C       *  GAMMAW = Unit weight of water, g/cm**3                        *
C       *  H = Soil thickness, cm                                        *
C       *  K = The coefficient of permeability, cm/sec                   *
C       *  UO = Initial uniform pore pressure, g/cm**2                   *
C       *  NOEL = Number of equal segments of the soil profile           *
C       *           specified for the outputs                            *
C       *  VDN(n) = Roots of eqn: JO(V).Y1(kV)-YO(V).J1(kV)=0            *
C       *              where k is the variable LAMBDA in the program     *
C       *  NORT = Total number of the above roots used                   *
C       *                                                                *
C       *  Use of the program:                                           *
C       *  1  First to compile the program by:                           *
C       *  RUN *FORTGTEST SCARDS=EDELMANN53 SPRINT=-1 PAR=ID,SOURCE      *
C       *  2  Repeat the following for subsequent executions:            *
C       *  DEBUG -LOAD#+*IMSLDPLIB 5=datafile 6=output                   *
C       *                                                                *
C       *  Remarks:                                                      *
C       *  The % consolidation computed is in terms of settlement        *
C       *  The routines MMBSJO, MMBSJ1 and MMBSYN in the IMSL            *
C       *  Library will be used  Their descriptions are shown at the     *
C       *  back of this program                                          *
C       *                                                                *
C       ******************************************************************
C
        IMPLICIT REAL*8(A-H,O-Z)
        REAL*8 LAMBDA,K,LIM,DSQRT,DFLOAT,DEXP,DLOG,MMBSJO,MMBSJ1
        INTEGER DIGIT(10)/'1','2','3','4','5','6','7','8','9','10'/
        INTEGER VF1(7)/'(5','X,7H','n   ','   =:','    ','(6X.','I2))'/
        INTEGER VF2(8)/'(5X,','7HTn','eta ','= 3X',',.','    ','F8.2',')'/
        DIMENSION VN(10),Z(100),BJOVN(10),YOVN(10),AN(10),EXPT(10)
        DIMENSION ALVN(10),AE(10),THETA(10),ZH(100),UE(100),YVN(2),YV(2)
C
C       ******************************************************************
C       *                                                                *
C       *  Read all input data                                           *
C       *                                                                *
C       ******************************************************************
C
        READ(5,50)T,SIGMAO,C,H,K
        READ(5,51)NOEL,NORT,UO,GAMMA,GAMMAW
        READ(5,52)(VN(I),I=1,NORT)
C
C       ******************************************************************
C       *                                                                *
C       *  Variable format input                                         *
C       *                                                                *
C       ******************************************************************
C
        VF1(5)=DIGIT(NORT)
        VF2(6)=DIGIT(NORT)
C
C       ******************************************************************
C       *                                                                *
C       *  Compute the average consolidation at the given time T         *
C       *  and the % error at time O   The theta terms are also          *
C       *  calculated                                                    *
C       *                                                                *
C       ******************************************************************
C
        ALPHA=SIGMAO/(C*GAMMA)
        HA1=H/ALPHA+1.DO
        LAMBDA=1.DO/DSQRT(HA1)
        TT=C*K*GAMMA*T/GAMMAW
C
        DHT=O.DO
        CONV=O.DO
C
        DO 20 I=1,NORT
        ALVN(I)=LAMBDA*VN(I)
        BJOVN(I)=MMBSJO(VN(I),IEJ1)
        BJOLVN=MMBSJO(ALVN(I),IEJ2)
        BJ1VN=MMBSJ1(VN(I),IEJ3)
        CALL MMBSYN(VN(I),O.DO,2,YVN,IEY1)
        CALL MMBSYN(ALVN(I),O.DO,1,YOLVN,IEY2)
        YOVN(I)=YVN(1)
        Y1VN=YVN(2)
        ZOLVN=BJOLVN-BJOVN(I)*YOLVN/YOVN(I)
        Z1VN=BJ1VN-BJOVN(I)*Y1VN/YOVN(I)
        AN(I)=2.DO*UO*ZOLVN/((VN(I)*Z1VN)**2-(ALVN(I)*ZOLVN)**2)
        THETA(I)=O.25DO*ALVN(I)*ALVN(I)*TT/ALPHA
        EXPT(I)=DEXP(-THETA(I))
        AE(I)=AN(I)*EXPT(I)
```

```
      DHT=DHT+AE(I)*ZOLVN
      CONV=CONV+AN(I)*ZOLVN/(2.DO*UO)
   20 CONTINUE
C
      LIM=DLOG(1.DO/LAMBDA)/2.DO
      ERR=(CONV-LIM)*100/LIM
C
      TEM=2.DO/(GAMMA*C)
      DELHF=TEM*UO*LIM*2.DO
      DELHT=DELHF-TEM*DHT
C
      AVCON=DELHT/DELHF
C
C     ****************************************************************
C     *                                                              *
C     *  Calculation of the excess pore pressure at various depth   *
C     *                                                              *
C     ****************************************************************
C
      NONOD=NOEL+1
      DIV=H/DFLOAT(NOEL)
      Z(1)=0.DO
C
      DO 25 J=1,NONOD
      Z(J+1)=Z(J)+DIV
      ZH(J)=Z(J)/H
      ZA1=Z(J)/ALPHA+1.DO
      UE(J)=0.DO
C
      DO 25 L=1,NORT
      V=ALVN(L)*DSQRT(ZA1)
      BJ1V=MMBSJ1(V,IEJ4)
      CALL MMBSYN(V,0.DO,2,YV,IEY3)
      Y1V=YV(2)
      Z1V=BJ1V-BJOVN(L)*Y1V/YOVN(L)
      UE(J)=UE(J)+AE(L)*V*Z1V
   25 CONTINUE
C
C     ****************************************************************
C     *                                                              *
C     *  Output quantities                                           *
C     *                                                              *
C     ****************************************************************
C
      WRITE(6,60)
      WRITE(6,61) AVCON,ERR
      WRITE(6,65) K,C,SIGMAO,H,GAMMA,GAMMAW,UO,ALPHA,LAMBDA,NORT,NOEL
      WRITE(6,62)T,(Z(I),ZH(I),I,UE(I),I=1,NONOD)
      WRITE(6,63)IEJ1,IEJ2,IEJ3,IEJ4,IEY1,IEY2,IEY3
      WRITE(6,64)
      WRITE(6,VF1)(N,N=1,NORT)
      WRITE(6,VF2)(THETA(J),J=1,NORT)
C
      STOP
C
C     ****************************************************************
C     *                                                              *
C     *  Format statments                                            *
C     *                                                              *
C     ****************************************************************
C
   50 FORMAT(5G20.0)
   51 FORMAT(2I5,3G20.0)
   52 FORMAT(3F20.0)
C
   60 FORMAT('1'////4X'The One Dimensional Consolidation with ',
     1'the Spatial Variation'/23X'of Compressibility'
     1//13X'Analytical Solution by Edelmann (1953)'///)
   62 FORMAT(13X'Excess pore pressure vs depth:'//
     113X'Depth',6X'Depth',4X'NODE',9X'Time t'/24X'Ratio',10XG20.9
     1//(9XF11.5,F10.4,3XI3,4XE15.8))
   61 FORMAT(4X'Average Consolidation =',F12.8
     1//4X'(Error of ave consol at time 0 =',F8.1,' %)'///)
   63 FORMAT(////5X'Error message from the *IMSLDPLIB for the final'
     1,' iteration:'//5X'IEJ1  IEJ2  IEJ3  IEJ4  IEY1  IEY2  IEY3'/
     12X7(2XI4))
   64 FORMAT(///5X'The theta terms:')
   65 FORMAT(4X'K       =',E15.6/4X'C       =',F15.5/
     14X'SIGMAO =',F15.5/4X'H       =',F15.5/
     14X'GAMMA  =',F15.5/4X'GAMMAW =',F15.5/
     14X'UO     =',F15.5//4X'Alpha  =',F15.5/
     14X'Lambda =',F15.5/4X'No of roots used =',I5/
     14X'No of elements    =',I5///)
C
C     ****************************************************************
C     *                                                              *
C     *                      # IMSL Library #                        *
C     *                                                              *
C     *  The following is a brief description of the Fortran         *
C     *  routines used in this program.  This information is         *
C     *  available in the IMSL Library reference manual, edition     *
C     *  8, 1980. The routines with single precision are stored      *
C     *  in the public file *IMSLLIB, those with double precision    *
C     *  are stored in *IMSLDPLIB.                                   *
C     *                                                              *
C     *                                                              *
C     *  Routine name:  MMBSJO                                       *
C     *                                                              *
C     *  Usage:  FUNCTION MMBSJO(ARG,IER)                            *
C     *                                                              *
C     *  Description of arguments:                                   *
C     *  ARG - Input argument                                        *
C     *  IER - Error parameter, terminal error                       *
C     *                                                              *
C     *                                                              *
C     *  Routine name:  MMBSJ1                                       *
```

```
C      *                                                                  *
C      *   Usage: FUNCTION MMBSJ1(ARG,IER)                                *
C      *                                                                  *
C      *   Description of arguments:                                      *
C      *   ARG - Input argument                                           *
C      *   IER - Error parameter, terminal error                          *
C      *                                                                  *
C      *                                                                  *
C      *   Routine name: MMBSYN                                           *
C      *                                                                  *
C      *   Usage: CALL MMBSYN(ARG,ORDER,N,YN,IER)                         *
C      *                                                                  *
C      *   Description of arguments:                                      *
C      *   ARG    - Input argument                                        *
C      *   ORDER - Desired order, which must be greater than or           *
C      *           equal to zero and less than one                        *
C      *   N      - Number of results required, with which order          *
C      *           start from 'ORDER' to 'ORDER+1' to 'ORDER+2', etc      *
C      *   YN     - Output vector of above results                        *
C      *   IER    - Error parameter where                                 *
C      *           '129': ORDER is out of range or ARG is less than       *
C      *                  the minimum allowable value                     *
C      *           '130': N is less than or equal to zero                 *
C      *           '131': YN overflow                                     *
C      *           '132': ARG is greater than the maximum allowable       *
C      *                  value                                           *
C      *                                                                  *
C      ********************************************************************
C
       END
```

B.5 Datafile A.20: Eq. A4

```
C     ***********************************************************************
C     *                                                                     *
C     *    #This program is to prepare part of the data for A.20(Eq.A4)     *
C     *     according to ADINAT users manual input section X.3 & X.4        *
C     * Variables: CC   = Cc/ln10                                           *
C     *            DIVU = load increment / number of material input points *
C     *            E    = void ratio                                        *
C     *            EO   = initial void ratio                                *
C     *            K    = coefficient of permeability, k;                   *
C     *                   or variable of "gamma*mv", where mv is the        *
C     *                   coefficient of volume compressibility             *
C     *            P    = effective stress                                  *
C     *            PO   = initial effective stress                          *
C     *            U    = excess pore pressure                              *
C     *            XL   = reduced depth, computed from Eq. 6.3 in text      *
C     * To use:  RUN *FORTGTEST SCARDS=file SPRINT=-1 PAR=id,source,map     *
C     *          DEBUG -LOAD# 5=data 6=output                               *
C     *                                                                     *
C     ***********************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 DLOG,DLOG10,K(500)
      DIMENSION U(500),XL(500)
      A=1.DO
      XL(1)=.1419DO
      XL(2)=.4592DO
      XL(3)=.8025DO
      XL(4)=1.1640DO
      XL(5)=1.5399DO
      XL(6)=1.9281DO
      XL(7)=2.3270DO
      XL(8)=2.7356DO
      XL(9)=3.1530DO
      XL(10)=3.5785DO
      XL(11)=4.0116DO
      XL(12)=4.4518DO
      XL(13)=4.8987DO
      XL(14)=5.3521DO
      XL(15)=5.8115DO
      XL(16)=6.2769DO
      XL(17)=6.7478DO
      XL(18)=7.2250DO
      XL(19)=7.7059DO
      XL(20)=8.1926DO
      CC=.4DO/DLOG(10.DO)
      DIVU=10.DO/20.DO
      U(1)=0.DO
      DO10II=1,20
   10 U(II+1)=U(II)+DIVU
      DO20I=1,20
      PO=.1DO+1.9DO*XL(I)
      EO=.9DO-.4DO*DLOG10(10.DO*PO)
      EO1=1.DO+EO
      DO30J=1,21
      P=PO+10.DO-U(J)
      K(J)=CC/(P*EO1)
   30 CONTINUE
      WRITE(6,60)I,A
      WRITE(6,61)(U(LL),LL=1,21),(K(JL),JL=1,21)
      WRITE(6,61)(U(LL),LL=1,21),(K(JL),JL=1,21)
   20 CONTINUE
      STOP
   60 FORMAT(3X,I2,F10.0)
   61 FORMAT(2(8F10.1/),5F10.1,3F10.9/3(8F10.9/))
      END
```

B.6 Datafile A.20: Eq. A8

```
C     ***********************************************************************
C     *                                                                     *
C     *    #This program is to prepare part of the data for A.20(Eq.A8)     *
C     *     according to ADINAT users manual input section X.3 & X.4        *
C     * Variables: CC   = Cc/ln10                                           *
C     *            DIVU = load increment / number of material input points  *
C     *            E    = void ratio                                        *
C     *            EO   = initial void ratio                                *
C     *            K    = variable of "k*(1+eo) / 1+e"                      *
C     *            MV   = variable of "gamma*mv*(1+e) / 1+eo"               *
C     *            P    = effective stress                                  *
C     *            PO   = initial effective stress                          *
C     *            U    = excess pore pressure                              *
C     *            XL   = reduced depth, computed from Eq. 6.3 in text      *
C     * To use:  RUN *FORTGTEST SCARDS=file SPRINT=-1 PAR=id,source,map     *
C     *          DEBUG -LOAD# 5=data 6=output                               *
C     *                                                                     *
C     ***********************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 DLOG,DLOG10,K(500),MV(500)
      DIMENSION U(500),XL(500)
      A=1.DO
      XL(1)=.1419DO
      XL(2)=.4592DO
      XL(3)=.8025DO
      XL(4)=1.1640DO
      XL(5)=1.5399DO
      XL(6)=1.9281DO
      XL(7)=2.3270DO
      XL(8)=2.7356DO
      XL(9)=3.1530DO
      XL(10)=3.5785DO
      XL(11)=4.0116DO
      XL(12)=4.4518DO
      XL(13)=4.8987DO
      XL(14)=5.3521DO
      XL(15)=5.8115DO
      XL(16)=6.2769DO
      XL(17)=6.7478DO
      XL(18)=7.2250DO
      XL(19)=7.7059DO
      XL(20)=8.1926DO
      CC=.4DO/DLOG(10.DO)
      DIVU=10.DO/20.DO
      U(1)=0.DO
      DO10II=1,20
   10 U(II+1)=U(II)+DIVU
      DO20I=1,20
      PO=.1DO+1.9DO*XL(I)
      EO=.9DO-.4DO*DLOG10(10*PO)
      EO1=1.DO+EO
      DO30J=1,21
      P=PO+10.DO-U(J)
      E=.9DO-.4DO*DLOG10(10*P)
      E1=1.DO+E
      MV(J)=CC/(P*EO1)
      K(J)=CC*EO1/(P*E1*E1)
   30 CONTINUE
      WRITE(6,60)I,A
      WRITE(6,61)(U(LL),LL=1,21),(K(JL),JL=1,21)
      WRITE(6,62)(U(LL),LL=1,21),(MV(JL),JL=1,21)
   20 CONTINUE
      STOP
   60 FORMAT(3X,I2,F10.0)
   61 FORMAT(2(8F10.1/),5F10.1,3F10.9/3(8F10.9/))
   62 FORMAT(2(8F10.1/),5F10.1,3F10.9/3(8F10.9/))
      END
```

B.7 Datafile A.20: Eq. A9

```
C      ******************************************************************
C      *                                                                *
C      *     #This program is to prepare part of the data for A.20(Eq.A9)   *
C      *      according to ADINAT users manual input section X.3 & X.4   *
C      * Variables: CC   =  Cc/ln10                                      *
C      *            DIVU =  load increment / number of interpolation points *
C      *            DIVZ =  reduced layer depth / number of elements      *
C      *            E    =  void ratio, e                                 *
C      *            K    =  variable of "k / 1+e"                         *
C      *            MV   =  variable of "gamma*mv*(1+e)"                  *
C      *            P    =  effective stress                              *
C      *            U    =  excess pore pressure                          *
C      *            Z    =  reduced coordinate, 'b'                       *
C      * To use:  RUN *FORTGTEST SCARDS=file SPRINT=-1 PAR=id,source,map  *
C      *          DEBUG -LOAD# 5=data 6=output                            *
C      *                                                                *
C      ******************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 DLOG,DLOG10,K(500),MV(500)
      DIMENSION U(500)
      A=1.DO
      DIVU=10.DO/20.DO
      U(1)=0.DO
      DO10II=1,20
   10 U(II+1)=U(II)+DIVU
      CC=.4DO/DLOG(10.DO)
      DIVZ=8.43786DO/20.DO
      Z=DIVZ/2.DO
      DO20I=1,20
      DO30J=1,21
      P=10.1DO+1.9DO*Z-U(J)
      E=.9DO-.4DO*DLOG10(10.DO*P)
      E1=1.DO+E
      MV(J)=CC/P
      K(J)=MV(J)/(E1*E1)
   30 CONTINUE
      WRITE(6,60)I,A
      WRITE(6,62)(U(LL),LL=1,21),(K(JJ),JJ=1,21)
      WRITE(6,61)(U(LL),LL=1,21),(MV(JJ),JJ=1,21)
      Z=Z+DIVZ
   20 CONTINUE
      STOP
   60 FORMAT(3X,I2,F10.0)
   61 FORMAT(2(8F10.1/),5F10.1,3F10.9/3(8F10.9/))
   62 FORMAT(2(8F10.1/),5F10.1,3F10.9/3(8F10.9/))
      END
```

B.8 Datafile A.21: Eq. A4

```
C     ***********************************************************************
C     *                                                                     *
C     *     #This program is to prepare part of the data for A.21(Eq.A4)    *
C     *      according to ADINAT users manual input section X.3 & X.4       *
C     * Variables: DIVU  =  load increment / number of material input points *
C     *            E     =  void ratio                                      *
C     *            EO    =  initial void ratio                              *
C     *            K     =  k ( = gamma*mv*Cv )                             *
C     *            MV    =  variable of "gamma*mv"                          *
C     *            P     =  effective stress                                *
C     *            POO   =  variable of "-lambda * initial effective stress" *
C     *            U     =  excess pore pressure                            *
C     *            XL    =  reduced depth: Eq.31 from Gibson etal (1981)    *
C     * To use:  RUN *FORTGTEST SCARDS=file SPRINT=-1 PAR=id,source,map     *
C     *          DEBUG -LOAD# 5=data 6=output                               *
C     *                                                                     *
C     ***********************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 DEXP,K(500),MV(500),XL(500)
      DIMENSION U(500)
      A=1.DO
      XL(1)=.0521DO
      XL(2)=.1587DO
      XL(3)=.2684DO
      XL(4)=.3813DO
      XL(5)=.4974DO
      XL(6)=.6168DO
      XL(7)=.7396DO
      XL(8)=.8658DO
      XL(9)=.995DO
      XL(10)=1.128DO
      XL(11)=1.265DO
      XL(12)=1.405DO
      XL(13)=1.548DO
      XL(14)=1.695DO
      XL(15)=1.845DO
      XL(16)=1.998DO
      XL(17)=2.155DO
      XL(18)=2.315DO
      XL(19)=2.477DO
      XL(20)=2.642DO
      DIVU=10.DO/20.DO
      U(1)=O.DO
      DO10II=1,20
   10 U(II+1)=U(II)+DIVU
      DO20I=1,20
      POO=-.332DO*1.74DO*XL(I)
      EO=1.49DO+2.34DO*DEXP(POO)
      EO1=1.DO+EO
      DO30J=1,21
      P=-.332DO*(1.74DO*XL(I)+10.DO-U(J))
      E=1.49DO+2.34DO*DEXP(P)
      AM=.332DO*(E-1.49DO)
      MV(J)=AM/EO1
      K(J)=MV(J)*.001944DO
   30 CONTINUE
      WRITE(6,60)I,A
      WRITE(6,61)(U(LL),LL=1,21),(K(JL),JL=1,21)
      WRITE(6,62)(U(LL),LL=1,21),(MV(JL),JL=1,21)
   20 CONTINUE
      STOP
   60 FORMAT(3X,I2,F10.0)
   61 FORMAT(2(8F10.1/),5F10.1,3E11.6/3(8E11.6/))
   62 FORMAT(2(8F10.1/),5F10.1,3F10.9/3(8F10.9/))
      END
```

B.9 Datafile A.21: Eq. A8

```
C     ************************************************************************
C     *                                                                      *
C     *    #This program is to prepare part of the data for A.21(Eq.A8)      *
C     *     according to ADINAT users manual input section X.3 & X.4         *
C     * Variables: DIVU = load increment / number of material input points  *
C     *            E    = void ratio                                         *
C     *            EO   = initial void ratio                                 *
C     *            K    = variable of "k*(1+eo) / 1+e"                       *
C     *            MV   = variable of "gamma*mv*(1+e) /(1+eo)"               *
C     *            P    = effective stress                                   *
C     *            POO  = variable of "-lambda * initial effective stress"  *
C     *            U    = excess pore pressure                               *
C     *            XL   = reduced depth: Eq.31 from Gibson etal (1981)       *
C     * To use:  RUN *FORTGTEST SCARDS=file SPRINT=-1 PAR=id,source,map      *
C     *          DEBUG -LOAD# 5=data 6=output                                *
C     *                                                                      *
C     ************************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 DEXP,K(500),MV(500),XL(500)
      DIMENSION U(500)
      A=1.DO
      XL(1)=.0521DO
      XL(2)=.1587DO
      XL(3)=.2684DO
      XL(4)=.3813DO
      XL(5)=.4974DO
      XL(6)=.6168DO
      XL(7)=.7396DO
      XL(8)=.8658DO
      XL(9)=0.995DO
      XL(10)=1.128DO
      XL(11)=1.265DO
      XL(12)=1.405DO
      XL(13)=1.548DO
      XL(14)=1.695DO
      XL(15)=1.845DO
      XL(16)=1.998DO
      XL(17)=2.155DO
      XL(18)=2.315DO
      XL(19)=2.477DO
      XL(20)=2.642DO
      DIVU=10.DO/20.DO
      U(1)=0.DO
      DO10II=1,20
   10 U(II+1)=U(II)+DIVU
      DO20I=1,20
      POO=-.332DO*1.74DO*XL(I)
      EO=1.49DO+2.34DO*DEXP(POO)
      EO1=1.DO+EO
      DO30J=1,21
      P=-.332DO*(1.74DO*XL(I)+10.DO-U(J))
      E=1.49DO+2.34DO*DEXP(P)
      E1=1.DO+E
      AM=.332DO*(E-1.49DO)
      MV(J)=AM/EO1
      K(J)=AM*.001944DO*EO1/(E1*E1)
   30 CONTINUE
      WRITE(6,60)I,A
      WRITE(6,61)(U(LL),LL=1,21),(K(JL),JL=1,21)
      WRITE(6,62)(U(LL),LL=1,21),(MV(JL),JL=1,21)
   20 CONTINUE
      STOP
   60 FORMAT(3X,I2,F10.0)
   61 FORMAT(2(8F10.1/),5F10.1,3E11.6/3(8E11.6/))
   62 FORMAT(2(8F10.1/),5F10.1,3F10.9/3(8F10.9/))
      END
```

B.10 Datafile A.21: Eq. A9

```
C     **********************************************************************
C     *                                                                    *
C     *     # This program is to prepare part of the data for A.21(Eq.A9)  *
C     *       according to ADINAT users manual input section X.3 & X.4     *
C     * Variables: DIVU =  load increment / number of interpolation points *
C     *            DIVZ =  reduced layer depth / number of elements        *
C     *            E    =  void ratio, e                                   *
C     *            K    =  variable of "k / 1+e"                           *
C     *            MV   =  variable of "gamma*mv*(1+e)"                    *
C     *            P    =  effective stress                                *
C     *            U    =  excess pore pressure                            *
C     *            Z    =  reduced coordinate, 'b'                         *
C     * To use:  RUN *FORTGTEST SCARDS=file SPRINT=-1 PAR=id,source,map    *
C     *          DEBUG -LOAD# 5=data 6=output                              *
C     *                                                                    *
C     **********************************************************************
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 DEXP,K(500),MV(500)
      DIMENSION U(500)
      A=1.DO
      DIVU=10.DO/20.DO
      U(1)=0.DO
      DO10II=1,20
   10 U(II+1)=U(II)+DIVU
      DIVZ=2.728DO/20.DO
      Z=DIVZ/2.DO
      DO20I=1,20
      DO30J=1,21
      P=-.332DO*(1.74DO*Z+10.DO-U(J))
      E=1.49DO+2.34DO*DEXP(P)
      E1=1.DO+E
      MV(J)=.332DO*(E-1.49DO)
      K(J)=MV(J)*.001944DO/(E1*E1)
   30 CONTINUE
      WRITE(6,60)I,A
      WRITE(6,61)(U(LL),LL=1,21),(K(JJ),JJ=1,21)
      WRITE(6,62)(U(LL),LL=1,21),(MV(JJ),JJ=1,21)
      Z=Z+DIVZ
   20 CONTINUE
      STOP
   60 FORMAT(3X,I2,F10.0)
   61 FORMAT(2(8F10.2/),5F10.2,3E11.6/3(8E11.6/))
   62 FORMAT(2(8F10.2/),5F10.2,3F10.9/3(8F10.9/))
      END
```